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The Effects of Small Changes in the Input Data on the Determination of Closed-Bomb Burning Rates and Surface Area

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13. ABSTRACT *(Maximum 200 words)*

In order to ascertain the effects of small changes in the input data on the determination of closed-bomb burning rates, a series of related computer programs was developed. The computer programs allow a qualitative and quantitative evaluation of the effects of varying thermodynamic properties and, if desired, the propellant grain dimensions. Program listings and sample runs are included, along with Fortran listings of common form functions.

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1. INTRODUCTION

A *closed bomb* is a fixed volume chamber in which gun propellant is burned. One purpose of a closed bomb is to collect pressure vs. time data, which allows the calculation of the linear burning rate (i.e., rate of grain regression). The burning rate can be determined from the known propellant geometry, the thermodynamic properties of the propellant, and the pressure-time curve.

In order to ascertain the effects of small changes in the input data on the determination of closed-bomb burning rates, a series of related computer programs was developed. The computer programs allow a qualitative and quantitative evaluation of the effects of varying thermodynamic properties and, if desired, the propellant grain dimensions. Similar capabilities have been provided in the new closed-bomb analysis program, BRLCB (Oberle and Kooker, to be published). Appendixes C, D, and E contain the source code listings for the computer programs PT, SURF, and BR. The computer programs are based on a previous procedure for the numerical simulation of a closed-bomb pressure-time curve (Robbins and Horst 1976). Each program requires the thermodynamic properties and two of the three input variables: 1) a pressure-time curve, 2) a surface area profile, and 3) a burning rate curve. The programs fix two of the three inputs; from these, information can be calculated for the third variable. Therefore, for the given thermodynamic properties of the propellant:

- the program PT calculates a set of pressure-time points from the surface area profile and the burning rate information;

- the program SURF calculates the surface area profile from the pressure-time and the burning rate information; and

- the program BR calculates a set of burning rates, pressure points from a given pressure-time curve, and a surface area profile.

The program PT is used to calculate the pressure vs. time curve from the baseline thermodynamic properties, surface area, and burning rate. Any of the input variables can be modified to assess the effect on the calculated burning rate or the calculated surface area.

For example, input variables can be modified to affect the grain geometry (i.e., perforation diameter, grain diameter, grain length, slot width, and density), or thermodynamic values (i.e., specific heat capacity, flame temperature, molecular weight, and covolume).

Two studies were conducted to determine how the modification of single variables affects the calculated burning rate and surface area of both single-perforated cylindrical slotted grains and 19-perforated cylindrical grains. Studies were performed to evaluate the effects of modifying the constant volume specific heat, grain diameter, perforation diameter, and the density of the propellant.

After studying how the modified variables influence the burning rate or surface area, the effects of the changed burning rate on interior ballistic calculation for a 120-mm and a 155-mm gun system were calculated.

2. DERIVATION OF EQUATIONS

If the igniter, air, and burned propellant gases completely mix, the following energy balance equation follows (see the List of Symbols):

$$m_i C_{vi}(FT_i - T) + m_p C_{vp}(FT_p - T) + m_a C_{va}(T_a - T) - L = 0 \tag{1}$$

where all energy losses are contained in L.

Solving Equation 1 for T, and assuming the igniter burns in the initial stage, one can write a covolume (Noble-Abel) equation of state in the following form:

$$\begin{aligned} & P\,[V_o - m_{po}/d_p + m_p(1/d_p - n_p) - m_i n_i - m_a n_a] \\ & = mR_h(m_p C_{vp} FT_p + m_i C_{vi} FT_i + m_a C_{va} T_a - L)/(m_p C_{vp} + m_i C_{vi} + m_a C_{va}) \end{aligned} \tag{2}$$

where

$$R_h = (R/mw_l + R/mw_a + R/mw_p)/m$$

$$= (R_l + R_a + R_p)/m$$

$$m = m_l + m_a + m_p .$$

A direct solution for P is allowed of the form:

$$P = f(m_p) . \tag{3}$$

With some rearrangement of terms, Equation 2 can be rewritten as a quadratic function of m_p:

$$Am_p^2 + Bm_p + C = 0 \tag{4}$$

where

$$A = P(1/d_p - n_p)C_{vp} - R_pC_{vp}FT_p$$

$$B = (m_lC_{vl} + m_aC_{va})P(1/d_p - n_p) + C_{vp}P(V_o - m_{po}/d_p - m_ln_l - m_an_a)$$
$$- C_{vp}FT_p(m_lR_l + m_aR_a) - R_p(m_lC_{vl}FT_l + m_aC_{va}T_a - L)$$

$$C = (-m_ln_l + V_o - mp_o/d_p - m_an_a)P(m_lC_{vl} + m_aC_{va})$$
$$-(m_lR_l + m_aR_a)(m_lC_{vl}FT_l + m_aC_{va}T_a - L) .$$

Hence, solutions can be found to the inverse problem of the form:

$$m_p = g(P) . \tag{5}$$

A solution for Equation 3 is required to simulate the pressure-time profile obtained by burning a given quantity of propellant in a closed chamber. This is obtained by making use of assumed or previously determined burning rate data and numerically integrating the standard burning rate "law" $dx/dt = aP^n$ to obtain a depth burned. A corresponding value for m_p is then generated in the conventional manner from the propellant geometry (form function). The assumptions employed include the complete burning of the igniter; instantaneous ignition of all propellant surfaces; and regression normal to these surfaces. In addition, an empirical energy loss description is employed as

$$DH = a + kP \tag{6}$$

where

$$DH = \text{Energy Loss up to time } t$$
$$P = P_t$$

and a and k are constants. In these studies, the value for a (an extra energy loss in the program) is set to zero. The value for k is obtained from the following:

$$k = (DH - a)/P_{max} = C_v m DT/P_{max} \tag{7}$$

where

$$C_v = (C_{vi}m_i + C_{vp}m_p + C_{va}m_a)/(m_i + m_p + m_a)$$

$$DT = d_{pmax}(V_o - m_i n_i - m_p n_p - m_a n_a)/mR_h$$

$$d_{pmax} = P_{THEO} - P_{max}.$$

An iterative procedure is required for the evaluation of k since the heat loss is a function of pressure, which is the value determined in the computer program PT. The proper pressure is assumed to have been calculated when the relative error is less than 10^{-5}.

To obtain the surface area one must know dm/dt. This is accomplished by determining two consecutive masses of burned propellant from the input p-t curve by using Equation 5 and creating a linear derivative. Then, using the computed burning rate at the current pressure, the surface area is computed from Equation 8:

$$S = (dm/dt) / (\rho * (dx/dt)) . \tag{8}$$

For the solution to the inverse problem (the standard burning rate reduction program), the computer program employs Equation 5, obtaining mass and referring to the form function to determine x (the distance burned into the propellant grain). Then two consecutive x's are used to form a numerical estimate of dx/dt. It should be mentioned that while dm/dt = f(P, dp/dt) could be obtained analytically, numerical differentiation of P would then be required.

3. CALCULATIONS FOR MODIFIED VARIABLES

The intended use of these interrelated programs is to discover the effect of changing a single parameter in a particular system. This should provide the user a better understanding to what extent error in the input data might influence the calculated surface area and burning rate (i.e., geometric error in measurements). The calculated value can then be compared with the known surface area or known burning rate. The user manual and the input databases, used to calculate the pressure-time curves, surface areas, and the burning rates, can be found in Appendix B.

The program PT calculates a set of pressure-time points from the surface area profile and the burning rate information. The pressure-time curve generated from this program is plotted and points are stored as an output file that will be used as input for the programs SURF and BR.

The program SURF generates a surface area profile from an input p-t file and the burning rate information. The surface area difference fraction (determined as the theoretical minus calculated surface area divided by the theoretical surface area) is also generated for easy comparison of the calculated and known theoretical surface areas. The theoretical surface area equations (form functions) can be found in Appendix A.

The program BR calculates a burning rate (r) vs. pressure (P) profile. A least-square fit of burning rate vs. pressure for the equation $r = aP^n$ can be fitted over different pressure ranges. This program uses the same input databases as SURF and PT, as well as the generated pressure-time curves from PT, as input.

Two studies have been performed as examples of the use of the computer programs. The first study used a slotted single-perforated grain (base.in) and the second used a 19-perforated right circular cylindrical grain (base1.in). To start the analysis, pressure-time curves were generated from the program PT. Figure 1 is a plot of the pressure time curve generated in PT using the "base1.in" input database (19-perforated right circular cylindrical grain) and Figure 2 is for "base.in" (slotted single-perforated grain).

The computer-generated p-t curves from PT (for different grains) may be used as input in the programs SURF and BR to check the precision of these programs. For the appropriate thermodynamics, the inverse calculations of surface areas and burning rates are performed. The precision of the computer-generated output compared against the known surface areas and burning rates is displayed in Table 1 for a slotted single-perforated and 19-perforated granulation. Plots of the calculated burning rates and the surface area difference fraction are given in Figures 3–6.

The influences of a 10.0% reduction of the specific heat capacity (CV), grain diameter (GRGD), perforation diameter (GRPD), and density (DEN) of the propellant have been calculated and investigated. The tabulated results include pressure, base value of the surface area and burning rate, value of the surface area and burning rate after the reduction, and the percent difference of the base value and value after the reduction. These results are shown in Tables 2 and 3.

Surface area difference fractions and the burning rate curves for the slotted single-perforated right circular cylindrical and for the 19-perforated right circular cylindrical grain are displayed for each reduction case in Figures 7–22. The one (1) added to the designator on the plots indicates a 19-perforated cylindrical grain.

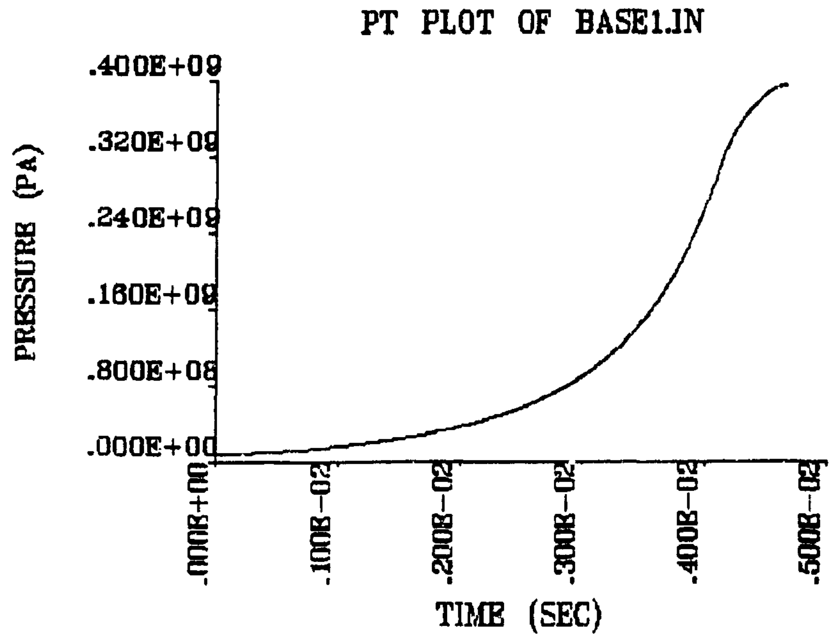

Figure 1. Pressure-Time Curve From the Baseline Case for the 19-Perforated Right Circular Cylindrical Grain.

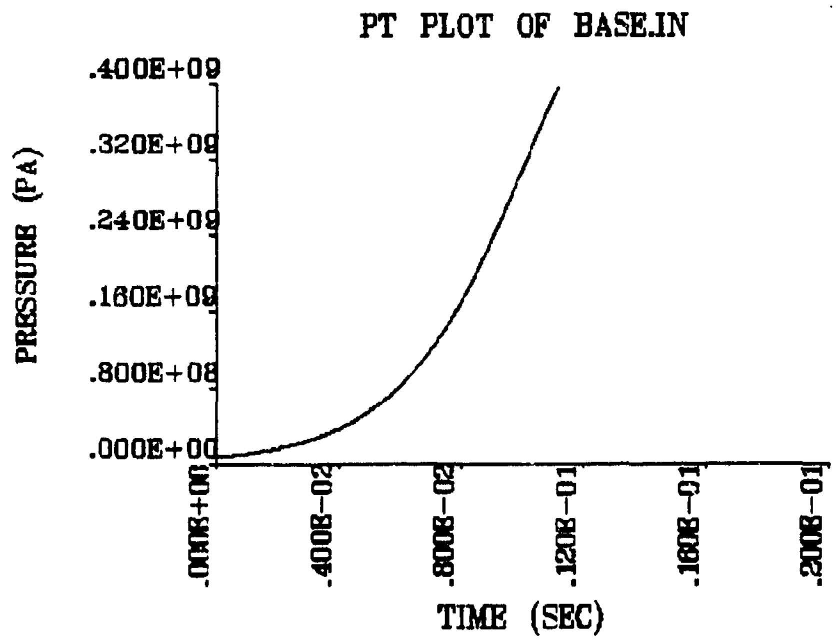

Figure 2. Pressure-Time Curve From the Baseline Case for the Slotted Single-Perforated Right Circular Cylindrical Grain.

Table 1. Analysis for the Precision of the Baseline Cases

Case Study	Computer Program	Pressure (MPa)	Given Known Surface Area (m^2)	Program Value Surface Area (m^2)	% Diff
SLOTTED	SURF	50	.0003825	.0003822	0.078
		100	.0003547	.0003547	0.000
		250	.0002637	.0002639	0.076
		350	.0001886	.0001888	0.106
19-PERF	SURF	50	.0007540	.0007533	0.093
		100	.0008236	.0008232	0.049
		250	.0009894	.0009888	0.061
		350	.0004683	.0004735	01.10
			Given Known Burning Rate (m/s)	Program Value Burning Rate (m/s)	
SLOTTED	BR	50	.0552595	.0554013	0.256
		100	.1105190	.1103527	0.150
		250	.2762975	.2759470	0.127
		350	.3868165	.3851048	0.443
19-PERF	BR	50	.0552595	.0552683	0.016
		100	.1105190	.1105305	0.010
		250	.2762975	.2763236	0.009
		350	.3868165	.3878025	0.254

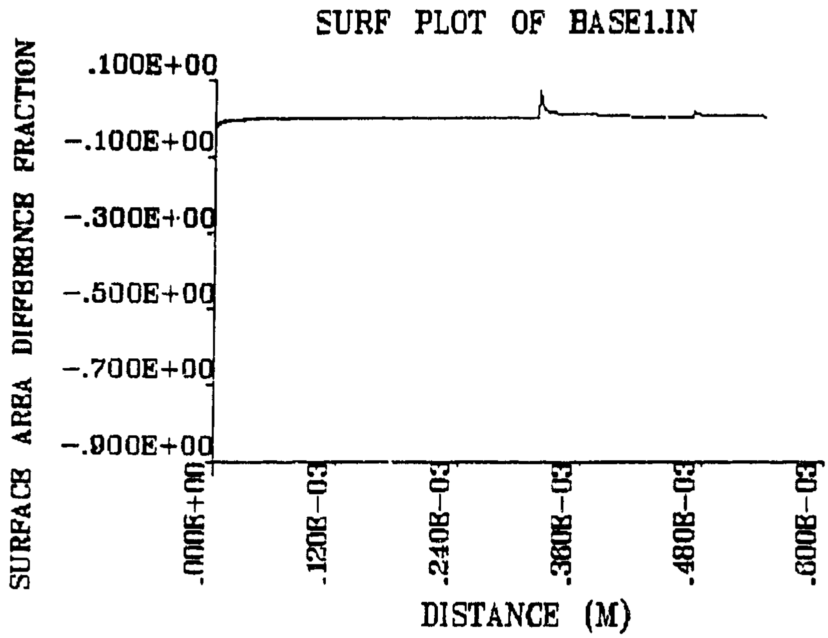

Figure 3. Surface Area Difference Fraction-Distance Curve for the 19-Perforated Right Circular Cylindrical Grain.

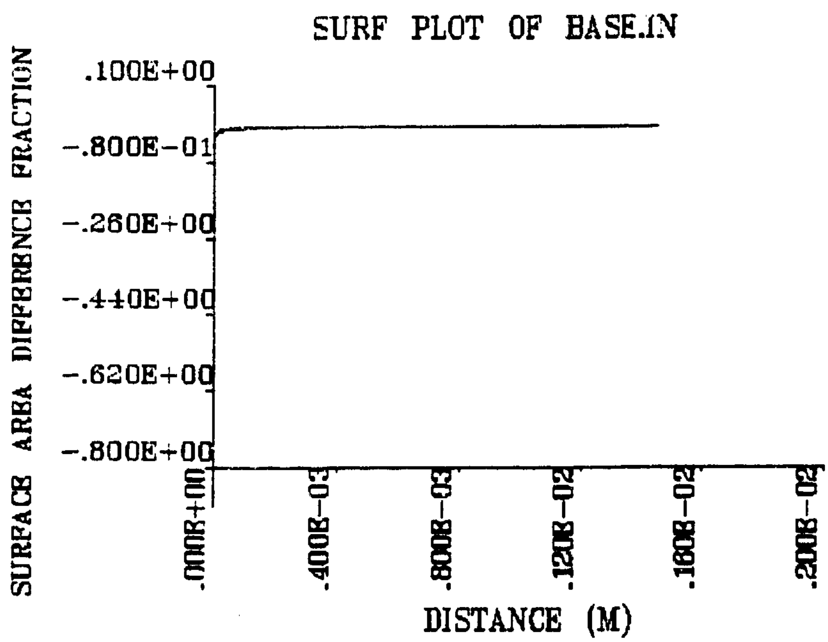

Figure 4. Surface Area Difference Fraction-Distance Curve for the Slotted Single-Perforated Right Circular Cylindrical Grain.

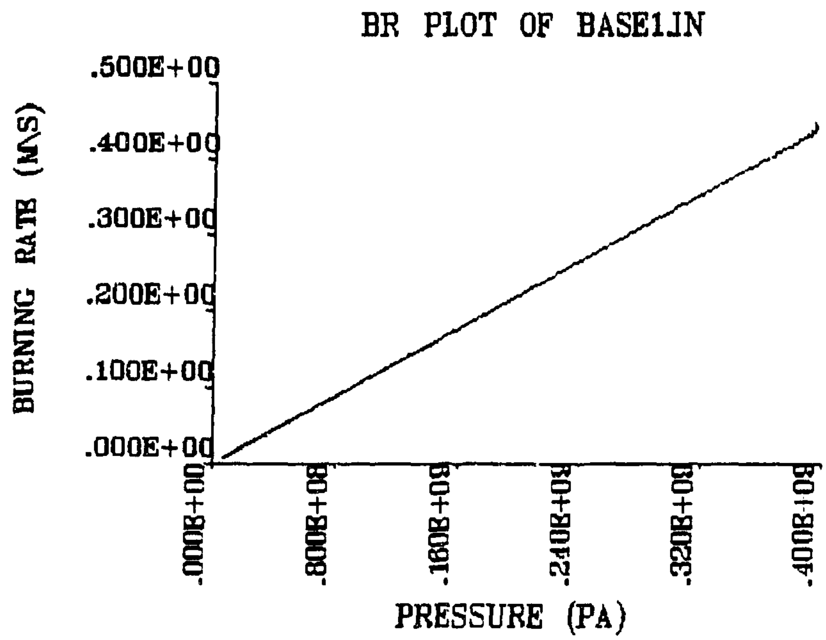

Figure 5. Burning Rate-Pressure Curve for the 19-Perforated Right Circular Cylindrical Grain.

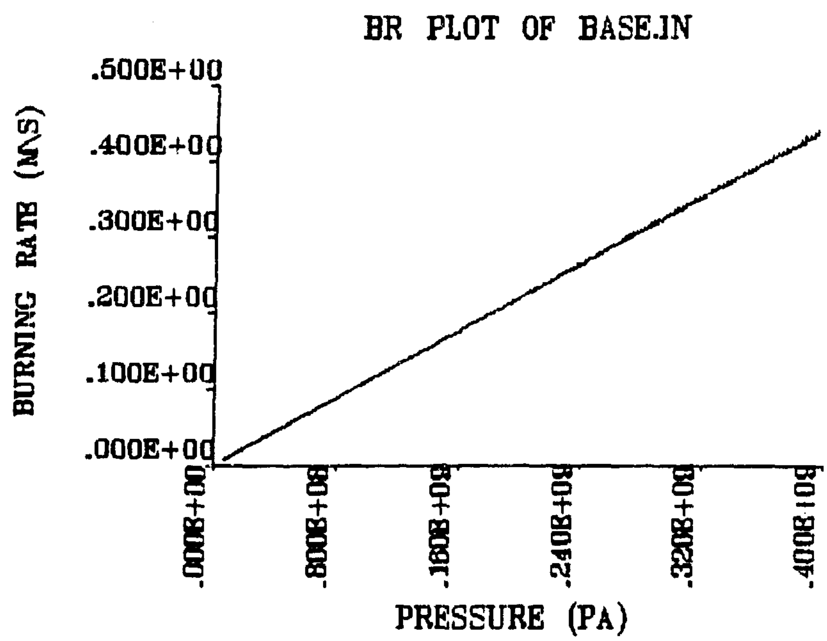

Figure 6. Burning Rate-Pressure Curve for the Slotted Single-Perforated Right Circular Cylindrical Grain.

Table 2. Analysis of the Surface Area of Modified Variables

Variable to be Changed	Reduction of the Variable (%)	Grain Type	Pressure (MPa)	Base Value Surface Area (m^2)	Value of Surface Area (m^2)	Program Diff Rate (%)
SPECIFIC HEAT	10.0	SLOTTED	50	.0003826	.0003822	0.105
			100	.0003547	.0003547	0.000
			250	.0002637	.0002639	0.076
			350	.0001886	.0001888	0.106
SPECIFIC HEAT	10.0	19-PERF	50	.0007540	.0007532	0.106
			100	.0008236	.0008233	0.049
			250	.0009894	.0009889	0.051
			350	.0004683	.0004736	01.12
GRAIN DIAMETER	10.0	SLOTTED	50	.0003388	.0003090	08.80
			100	.0003124	.0002868	08.19
			250	.0002261	.0002134	05.62
			350	.0001528	.0001526	0.065
GRAIN DIAMETER	10.0	19-PERF	50	.0007174	.0005907	17.66
			100	.0007876	.0006456	18.03
			250	.0008865	.0007754	12.53
			350	.0002499	.0003713	32.70
PERFORATION DIAMETER	10.0	SLOTTED	50	.0003814	.0003826	0.314
			100	.0003536	.0003551	0.422
			250	.0002629	.0002642	0.492
			350	.0001879	.0001890	0.582
PERFORATION DIAMETER	10.0	19-PERF	50	.0007182	.0007728	07.07
			100	.0007885	.0008445	06.63
			250	.0009561	.0010143	05.74
			350	.0005850	.0004857	16.97
DENSITY OF PROPELLANT	10.0	SLOTTED	50	.0003827	.0003718	02.85
			100	.0003548	.0003485	01.78
			250	.0002639	.0002667	01.05
			350	.0001887	.0001943	02.88
DENSITY OF PROPELLANT	10.0	19-PERF	50	.0007536	.0007382	02.04
			100	.0008232	.0008087	01.76
			250	.0009890	.0009991	01.01
			350	.0004702	.0004874	03.53

Table 3. Analysis of the Burning Rate of Modified Variables

Variable to be Changed	Reduction of the Variable (%)	Grain Type	Pressure (MPa)	Given Known Burning Rate (m/s)	Value of Burning Rate (m/s)	Program Diff Rate (%)
SPECIFIC HEAT	10.0	SLOTTED	50	.0552595	.0552328	0.048
			100	.1105190	.1103581	0.146
			250	.2762975	.2753570	0.340
			350	.3868165	.3879912	0.303
SPECIFIC HEAT	10.0	19-PERF	50	.0552595	.0552727	0.024
			100	.1105190	.1105478	0.026
			250	.2762975	.2763681	0.026
			350	.3868165	.3878083	0.256
GRAIN DIAMETER	10.0	SLOTTED	50	.0552595	.0501016	09.33
			100	.1105190	.1001044	09.42
			250	.2762975	.2465141	10.78
			350	.3868165	.3381188	12.59
GRAIN DIAMETER	10.0	19-PERF	50	.0552595	.0462781	12.59
			100	.1105190	.0932511	16.29
			250	.2762975	.2356334	14.72
			350	.3868165	.3510377	09.25
PERFORATION DIAMETER	10.0	SLOTTED	50	.0552595	.0556754	0.747
			100	.1105190	.1110111	0.443
			250	.2762975	.2771824	0.319
			350	.3868165	.3902079	0.869
PERFORATION DIAMETER	10.0	19-PERF	50	.0552595	.0590937	06.49
			100	.1105190	.1170415	05.57
			250	.2762975	.2883547	04.18
			350	.3868165	.3861553	0.171
DENSITY OF PROPELLANT	10.0	SLOTTED	50	.0552595	.0538193	02.61
			100	.1105190	.1078383	02.43
			250	.2762975	.2774611	0.419
			350	.3868165	.3968464	02.53
DENSITY OF PROPELLANT	10.0	19-PERF	50	.0552595	.0539383	02.39
			100	.1105190	.1090565	01.32
			250	.2762975	.2801590	01.38
			350	.3868165	.3871016	0.074

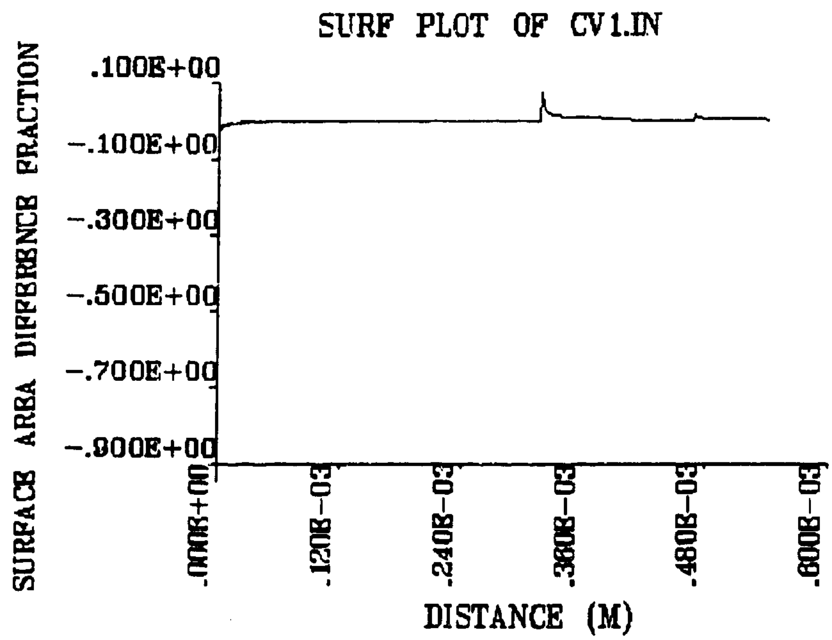

Figure 7. Surface Area Difference Fraction-Distance Curve With a 10% Reduction of the Specific Heat Capacity for the 19-Perforated Right Circular Cylindrical Grain.

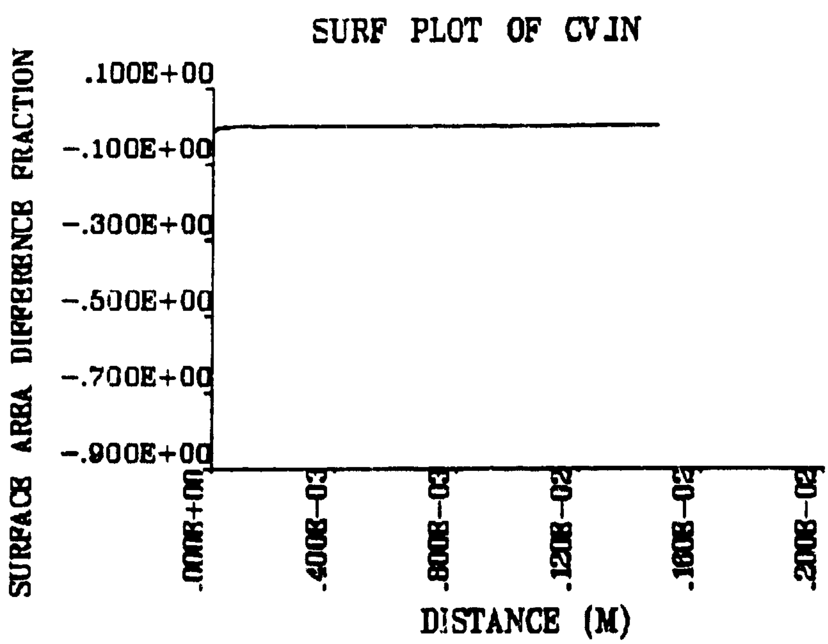

Figure 8. Surface Area Difference Fraction-Distance Curve With a 10% Reduction of the Specific Heat Capacity for the Slotted Single-Perforated Right Circular Cylindrical Grain.

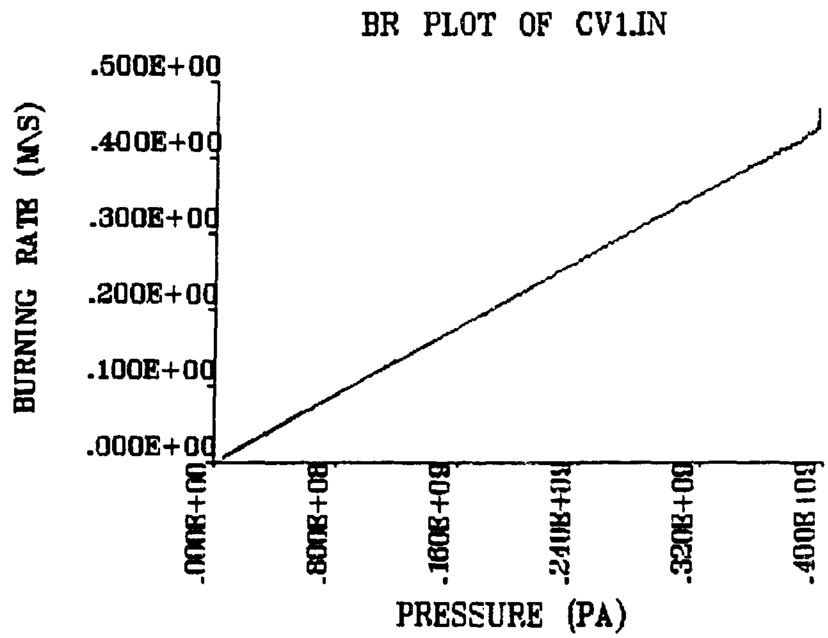

Figure 9. Burning Rate-Pressure Curve With a 10% Reduction of the Specific Heat Capacity for the 19-Perforated Right Circular Cylindrical Grain.

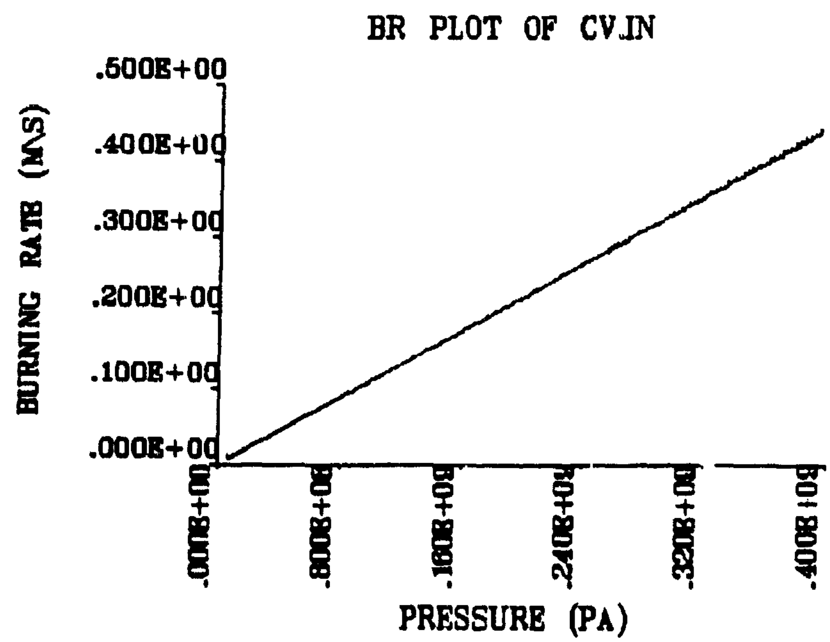

Figure 10. Burning Rate-Pressure Curve With a 10% Reduction of the Specific Heat Capacity for the Slotted Single-Perforated Right Circular Cylindrical Grain.

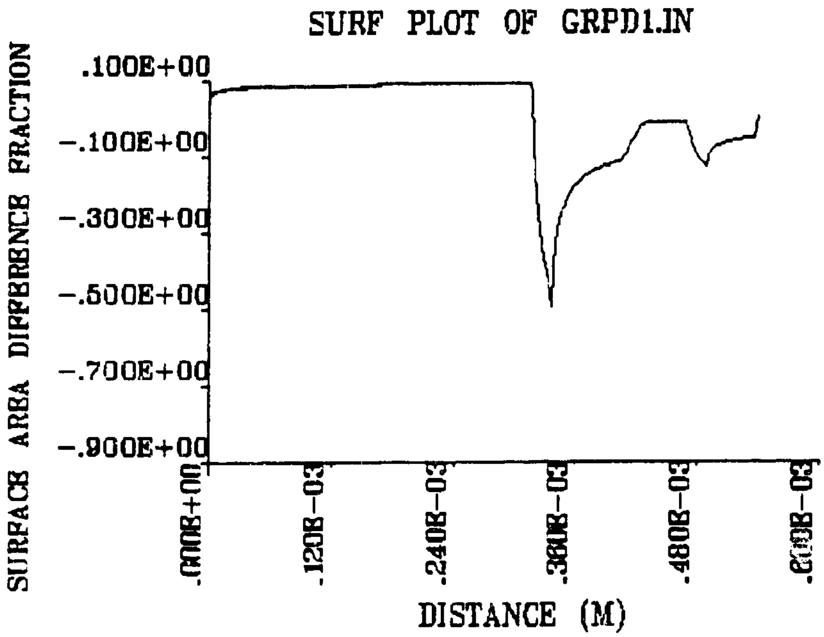

Figure 11. Surface Area Difference Fraction-Distance Curve With a 10% Reduction of the Perforation Diameter for the 19-Perforated Right Circular Cylindrical Grain.

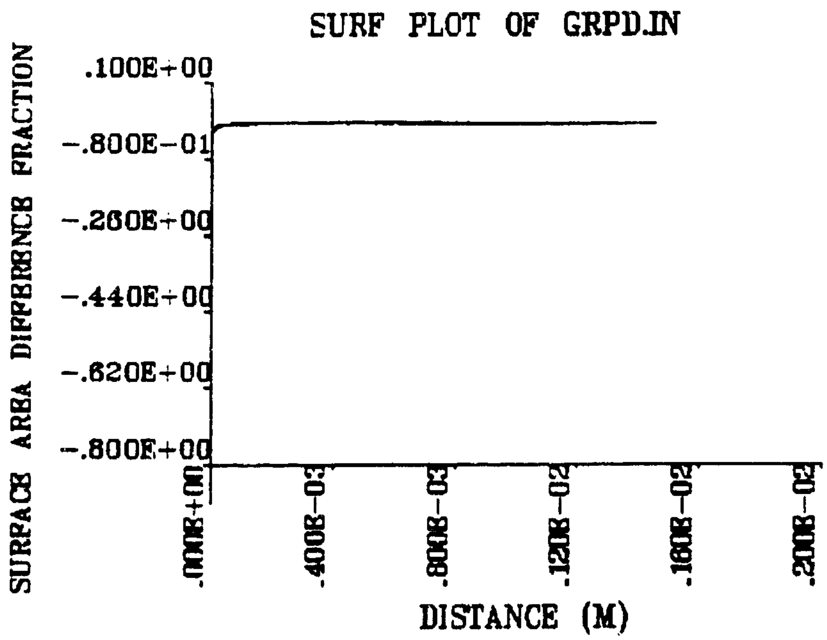

Figure 12. Surface Area Difference Fraction-Distance Curve With a 10% Reduction of the Perforation Diameter for the Slotted Single-Perforated Right Circular Cylindrical Grain.

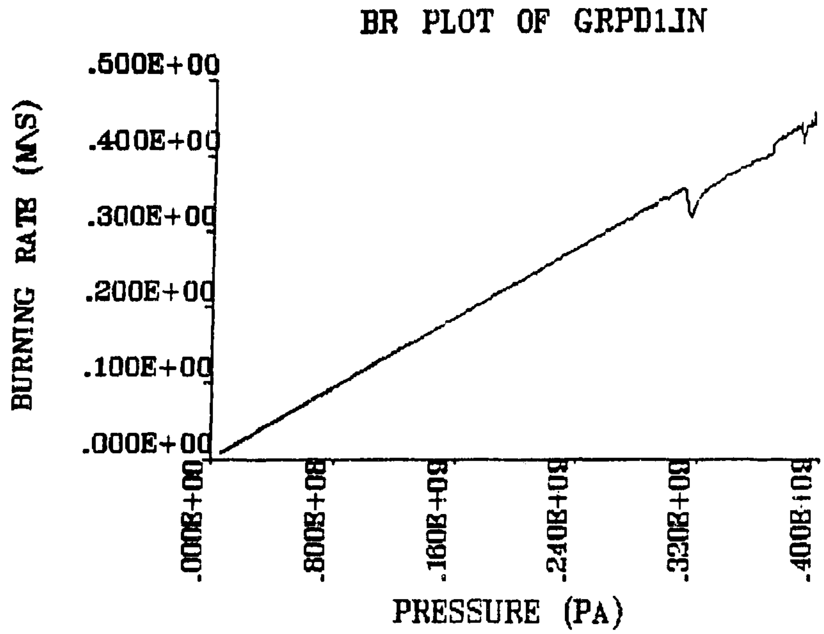

Figure 13. Burning Rate-Pressure Curve With a 10% Reduction of the Perforation Diameter for the 19-Perforated Right Circular Cylindrical Grain.

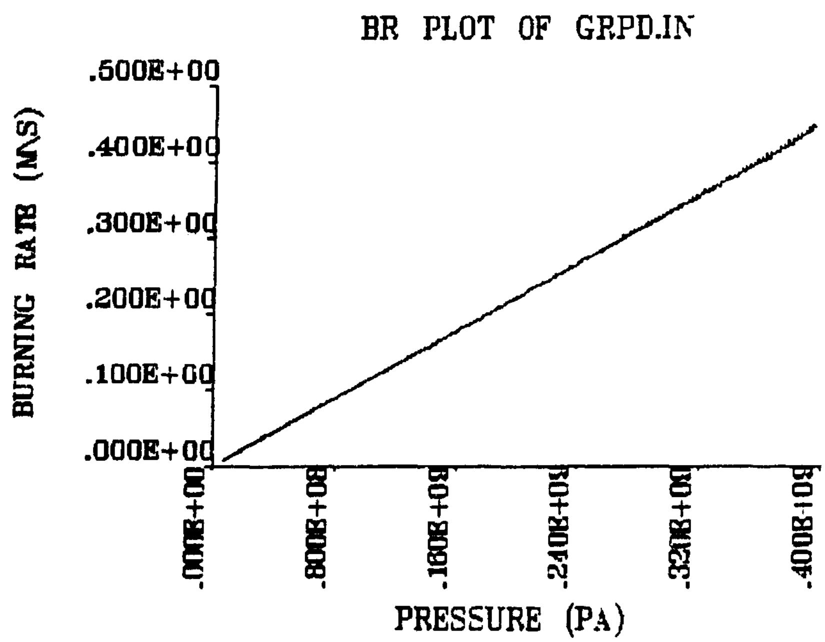

Figure 14. Burning Rate-Pressure Curve With a 10% Reduction of the Perforation Diameter for the Slotted Single-Perforated Right Circular Cylindrical Grain.

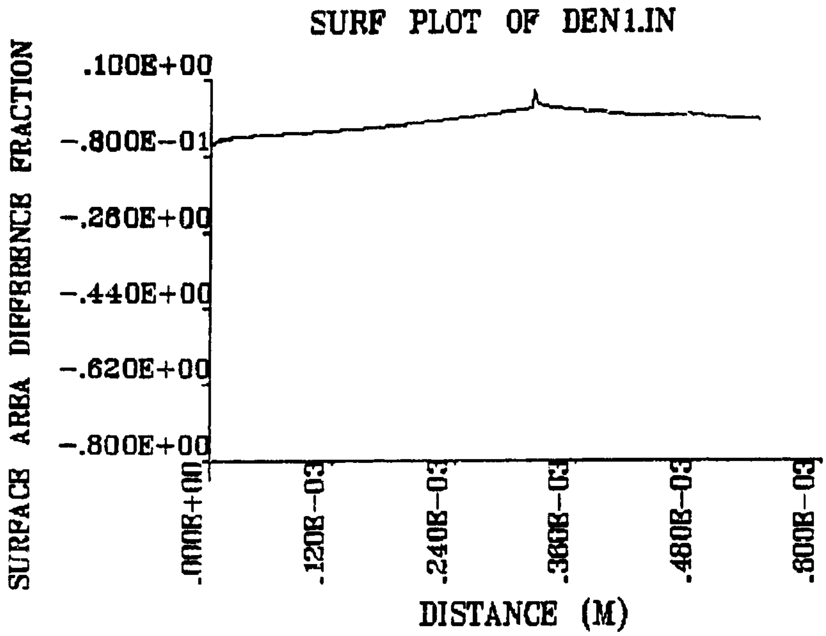

Figure 15. Surface Area Difference Fraction-Distance Curve With a 10% Reduction of the Propellant Density for the 19-Perforated Right Circular Cylindrical Grain.

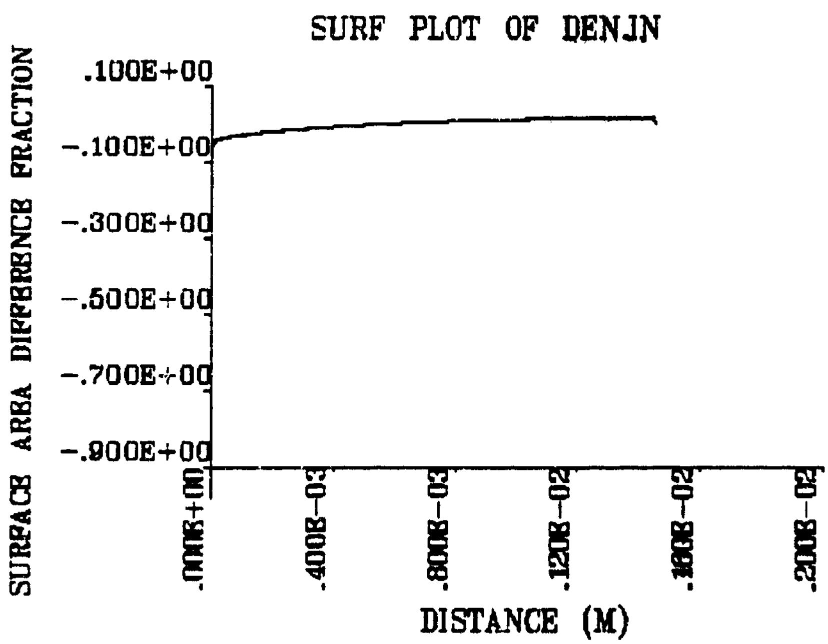

Figure 16. Surface Area Difference Fraction-Distance Curve With a 10% Reduction of the Propellant Density for the Slotted Single-Perforated Right Circular Cylindrical Grain.

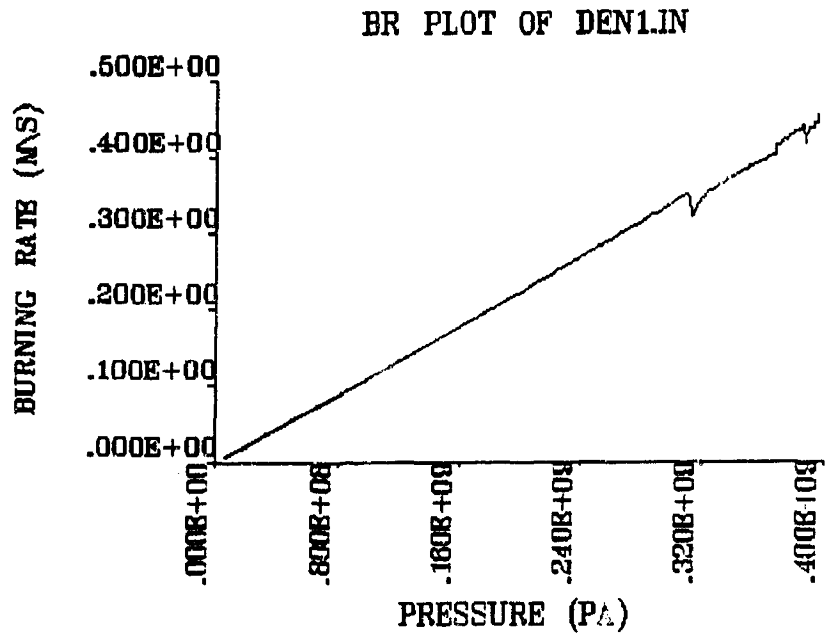

Figure 17. Burning Rate-Pressure Curve With a 10% Reduction of the Propellant Density for the 19-Perforated Right Circular Cylindrical Grain.

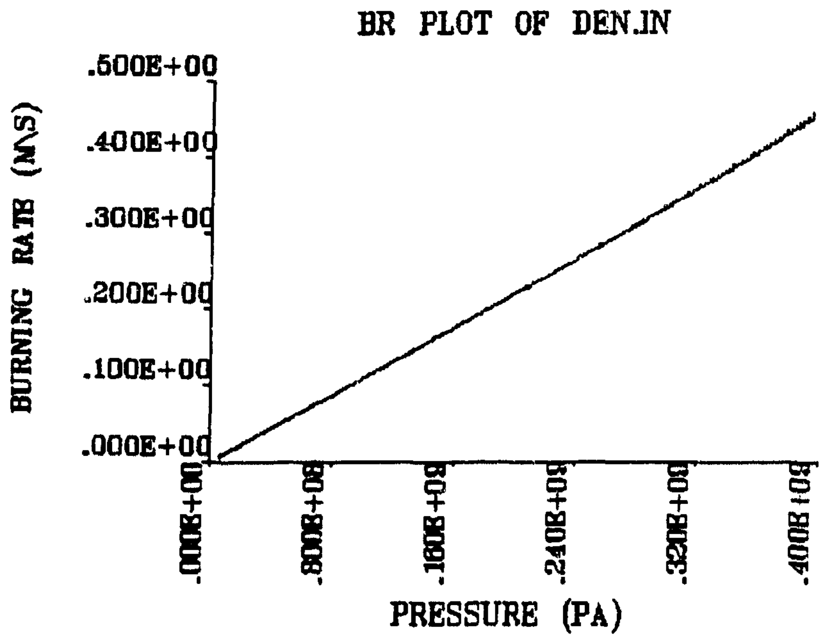

Figure 18. Burning Rate-Pressure Curve With a 10% Reduction of the Propellant Density for the Slotted Single-Perforated Right Circular Cylindrical Grain.

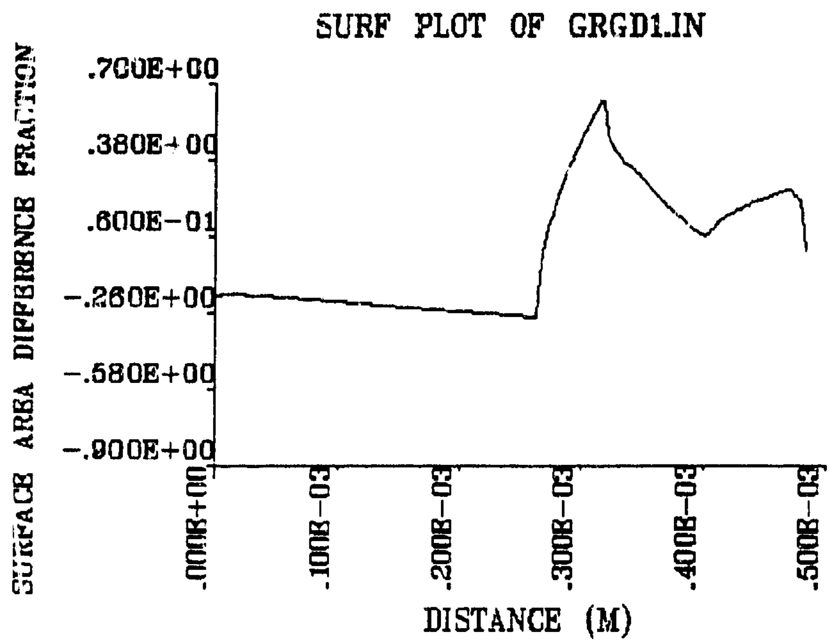

Figure 19. Surface Area Difference Fraction-Distance Curve With a 10% Reduction of the Grain Diameter for the 19-Perforated Right Circular Cylindrical Grain.

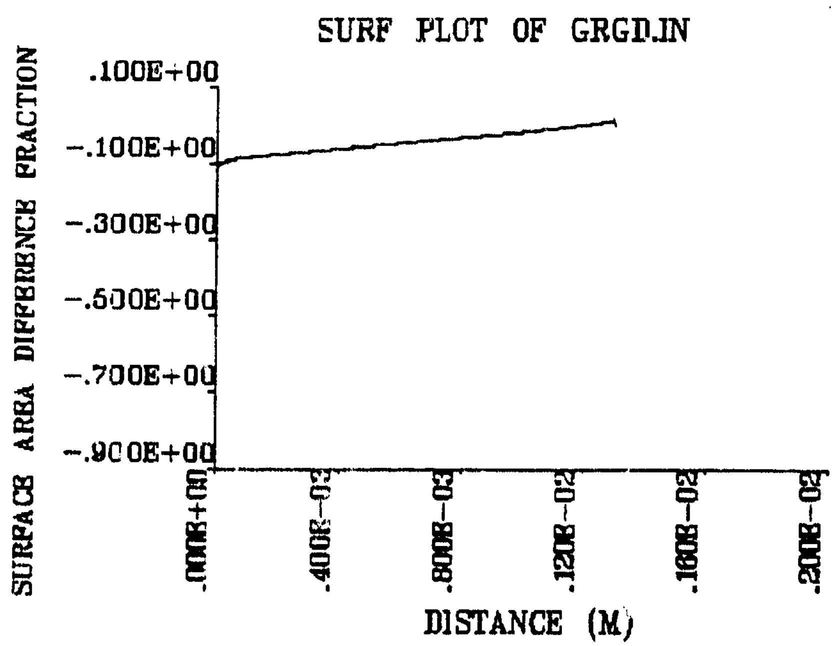

Figure 20. Surface Area Difference Fraction-Distance Curve With a 10% Reduction of the Grain Diameter for the Slotted Single-Perforated Right Circular Cylindrical Grain.

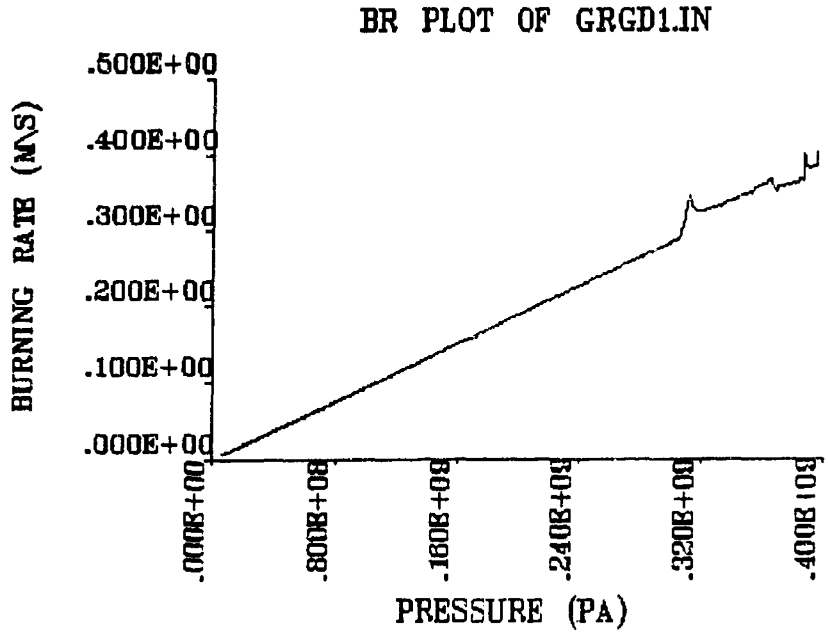

Figure 21. Burning Rate-Pressure Curve With a 10% Reduction of the Grain Diameter for the 19-Perforated Right Circular Cylindrical Grain.

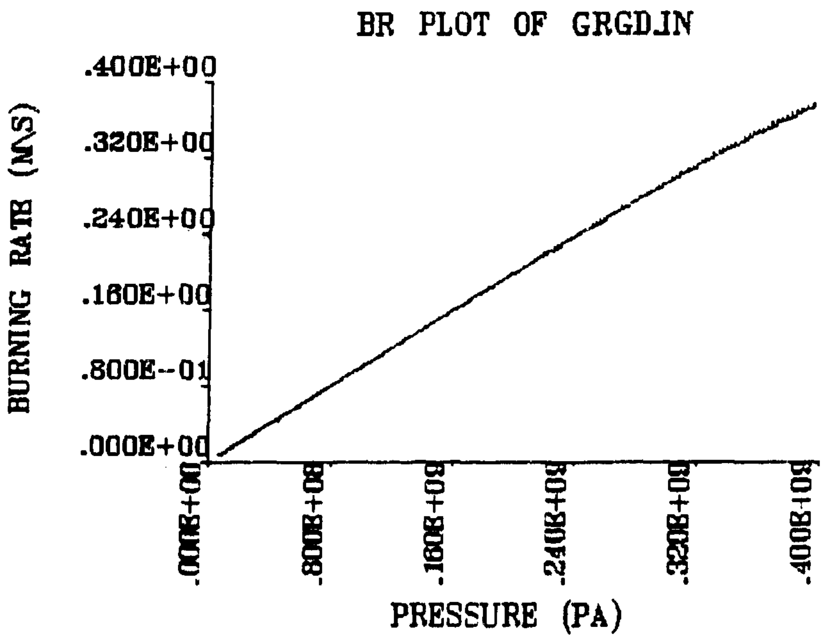

Figure 22. Burning Rate-Pressure Curve With a 10% Reduction of the Grain Diameter for the Slotted Single-Perforated Right Circular Cylindrical Grain.

4. CALCULATIONS FOR APPLICATION ANALYSIS

Interpreting the data is an important element of these case studies. Using IBHVG2 (Anderson and Fickie 1987), an analysis was performed to demonstrate the influence of the reduction of the burning rate on a 120-mm and 155-mm gun system. Shown in Table 4 are the calculated effects of the reduction in the burning rate on the maximum breech pressure and the exit velocity. Note the variable which may have caused a burning rate reduction was not changed in the IB database.

5. ADDITIONAL NOTES

The form function subroutine is provided and documented and can be used to calculate the volume, surface area, mass fraction, and ds/dx. Ds/dx is the rate of the change of the propellant surface area with respect to distance burned into the propellant, and is required with more complicated gradient equations used in lumped-parameter interior ballistic codes (Robbins, Anderson, and Gough 1990).

It was discovered that the first few calculated points in the burning rate analysis are often different by as much as the maximum calculated burning rate. These discrepancies are attributed to numerical problems with the solution techniques.

6. CONCLUSION

Three computer programs were developed to provide an analysis of the closed-bomb burning rate data—they are PT, SURF, and BR. PT is used to calculate a set of pressure-time points from the surface area profile and the burning rate information based on the given thermodynamic data. Calculation with SURF provides the surface area profile from the pressure-time curve and the burning rate information. And, with BR, a set of burning rates is calculated from the pressure-time curve and the surface area profile. The computer programs allow calculations of the effects of changes in variables on the determination of the burning rates and the surface areas for a closed-bomb system.

Table 4. Effects of Burning Rate in Gun Systems

Gun System	Burn Rate Reduction (%)	Grain Type	Breech Pressure (MPa)	Velocity (m/s)
120-mm	0	slotted	500.03	1,765.44
	5	slotted	451.06	1,721.76
	10	slotted	404.49	1,668.47
	0	19-perf	499.52	1,746.54
	5	19-perf	451.06	1,701.49
	10	19-perf	423.66	1,645.98
155-mm	0	slotted	344.99	746.03
	5	slotted	313.61	722.56
	10	slotted	283.60	693.53
	0	19-perf	344.23	743.70
	5	19-perf	307.81	720.43
	10	19-perf	273.60	692.44

Examples of the use of the program are given and demonstrate a large difference in the calculated burning rates and surface areas for the same percent change in the variable. An error of 10% in the calculated burning rate could result in errors as large as 20% in gun interior ballistic calculations.

7. REFERENCES

Anderson, R. D., and K. D. Fickie. "IBHVG2--A User's Guide." BRL-TR-2829, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1987.

Oberle, W. F., and D. E. Kooker. "BRLCB A Closed Chamber Data Analysis Program Theory and Users Manual." U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD (to be published).

Robbins, F. W., R. D. Anderson, and P. S. Gough. "New Pressure Gradient Equations for Lumped-Parameter Interior Ballistic Codes." BRL-TR-3097, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, May 1990.

Robbins, F. W., and A. W. Horst. "Numerical Simulations of Closed Bomb Performance Based on BLAKE CODE Thermodynamic Data." IHMR 76-259, Naval Ordnance Station, Indian Head, MD, 29 November 1976.

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APPENDIX A:

FORM FUNCTION EQUATIONS

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Closed-bomb and interior ballistic computer codes require the surface area and/or the volume of the propellant grains as a function of depth burned into the propellant grain. This relationship is known as the *form function* for that granulation. The following is a series of form functions for specific grain types. They are: spherical, rectangular, right circular cylindrical, 1-perforated right circular cylindrical, 7-perforated right circular cylindrical, 19-perforated right circular cylindrical, 19-perforated right hexagonal with rounded corners, and a slotted single-perforated right circular cylindrical grain type.

It is assumed that the grains are of a constant density, perfectly symmetrical, and that the propellant grains all burn normal to all exposed surfaces. Burnout occurs under either of two conditions: the first condition is when the propellant is burned through from the ends, and the second condition is when the propellant is burned through from the lateral direction.

The form function subroutine, FORMFN, relies on an input consisting of all numerical parameters essential for running the code. Values may be in metric or in imperial units, but must be consistent throughout.

It is not normally necessary to calculate ds/dx, the change of the surface area with respect to distance burned, for standard closed bomb and interior ballistic codes. But ds/dx may be required when considering more advanced gradient equations and so are provided for all of the form functions. These are exact up to the slivering phase and approximations thereafter.

The analytic derivations for the surface area and the volume of the 7-perforated right circular cylindrical, 19-perforated right circular cylindrical, and 19-perforated right hexagonal grain with rounded corner types are based on the unpublished work of Jim Kudzal, August 1975, Naval Ordnance Station, Indian Head, MD.

The analytic derivations for the extension of the surface area and the volume of a 19-perforated right hexagonal grain to the one with rounded corners is based on the unpublished work of Glenn M. Mason, June 1985, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD.

The equations for the initial volume, volume, mass fraction, surface area, and ds/dx of a spherical grain type (Figure A-1) where x is the distance burned, are:

$$V_o = 4./3. * pi * (gd/2.)^3$$

$$V = 4./3. * pi * (gd/2. - x)^3$$

$$frac = 1. - V/V_o$$

$$S = 4. * pi * (gd/2. - x)^2$$

$$ds/dx = -8. * pi * (gd/2. - x)$$

At burn out:

$$V = 0.$$

$$frac = 1.$$

$$S = 0.$$

$$ds/dx = 0.$$

The equations for a rectangular grain type (Figure A-2) are:

$$V_o = w * h * gl$$

$$V = (w - 2. * x) * (h - 2. * x) * (gl - 2. * x)$$

$$frac = 1. - V/V_o$$

$$S = 2. * (w - 2. * x) * (h - 2. * x) + 2. * (h - 2. * x) * (gl - 2. * x) + 2. * (w - 2. * x) * (gl - 2. * x)$$

$$ds/dx = 2. * (-4. * w + 8. * x) + 2. * (-4. * h + 8. * x) + 2. * (-4 * gl + 8. * x)$$

At burn out:

$$V = 0.$$

$$frac = 1.$$

$$S = 0.$$

$$ds/dx = 0.$$

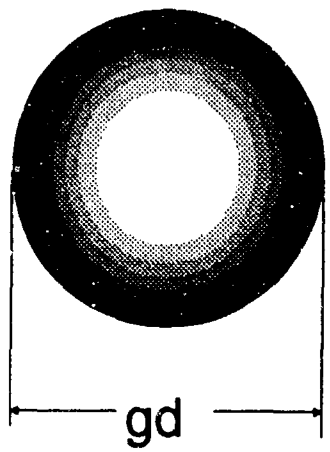

Figure 1-A. Spherical Grain.

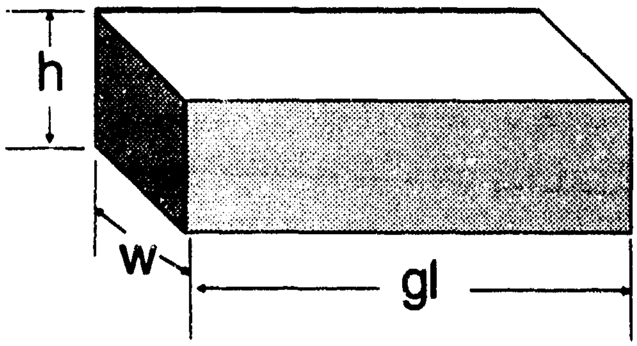

Figure 2-A. Rectangular Grain.

The equations for a right circular cylindrical grain type (Figure 3-A) are:

$$V_o = pi * gd * gd/4. * gl$$

$$V = pi * (gd - 2. * x)^2/4. * (gl - 2. * x)$$

$$frac = 1. - V/V_o$$

$$S = pi/2. * (gd - 2. * x)^2 + pi * (gd - 2. * x) * (gl - 2 * x)$$

$$ds/dx = -2. * pi * (2 * gd + gl - 6. * x)$$

At burn out:

$$V = 0.$$

$$frac = 1.$$

$$S = 0.$$

$$ds/dx = 0.$$

The equations for a single-perforated right circular cylindrical grain type (Figure 4-A) with equal webs, where x is the distance burned, are:

$$V_o = pi/4. * (gd * gd - pd * pd) * gl$$

$$V = pi/4. * ((gd - 2. * x)^2 - (pd + 2. * x)^2) * (gl - 2. * x)$$

$$frac = 1. - V/V_o$$

$$S = pi/2. * ((gd - 2. * x)^2 - (pd + 2. * x)^2) + pi * (gd - 2. * x) * (gl - 2. * x) + pi * (pd + 2. * x) * (gl - 2. * x)$$

$$ds/dx = -4. * pi * (gd + pd)$$

At burn out:

$$V = 0.$$

$$frac = 1.$$

$$S = 0.$$

$$ds/dx = 0.$$

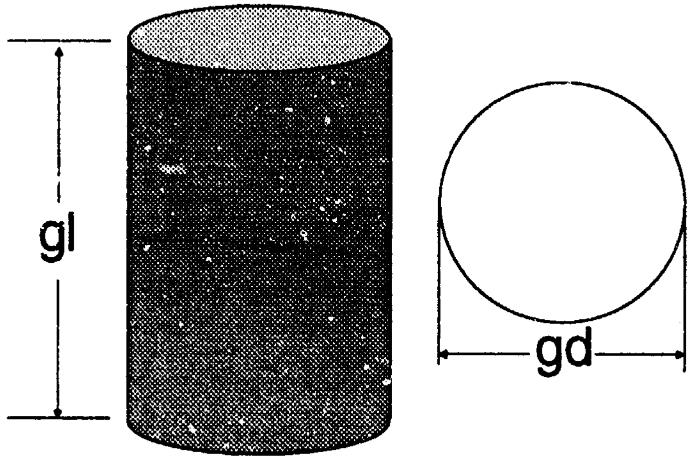

Figure 3-A. <u>Right Circular Cylindrical Grain.</u>

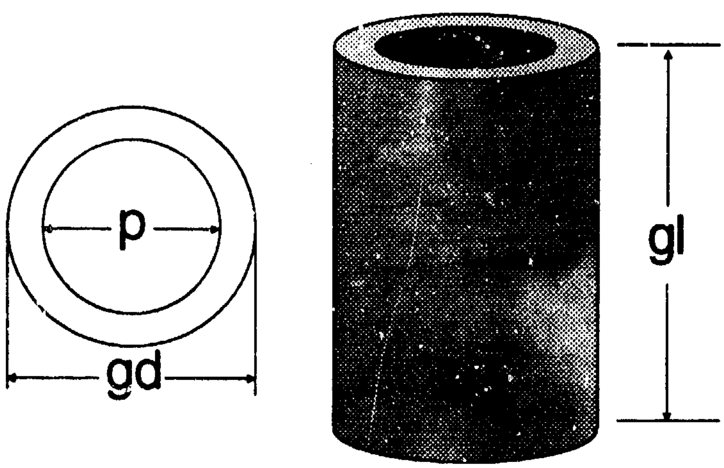

Figure 4-A. <u>Single-Perforated Right Circular Cylindrical Grain.</u>

The equations for a 7-perforated right circular cylindrical grain type (Figure A-5) with equal webs and perforations, where x is the distance burned, are:

For: $x \leq .5 * web$

$$V_o = pi/4. * gl * (gd * gd - 7. * pd * pd)$$

$$V = pi/4. * (gl - 2. * x) * ((gd - 2. * x)^2 - 7. * (pd + 2. * x)^2)$$

$$frac = 1. - V/V_o$$

$$S = 2. * V/(gl - 2. * x) + pi * (gl - 2. * x) * ((gd - 2. * x) + 7. * (pd + 2. * x))$$

$$ds/dx = -4. * pi * (gd + 7. * pd - 3. * gl + 18. * x)$$

For: $x > .5 * web$ (after slivering)

$$V = V_1 + V_2$$

$$frac = 1. - V/V_o$$

$$S = S_1 + S_2$$

$$ds/dx = -S/(X_2 - x) \quad \text{(approximately)}$$

For: $.5 * web < x < X_1$ (up to where the inner sliver burns out)

$$V_1 = 3./4. * (gl - 2. * x) * (2. * sqrt3 * d^2 - pi * (pd + 2. * x)^2 + 24. * a_1)$$

$$S_1 = (2. * V_1/(gl - 2. * x)) + 3. * (gl - 2. * x) * (pi - 6. * theta) * (pd + 2. * x)$$

For: $x \geq X_1$

$$V_1 = 0.$$

$$S_1 = 0.$$

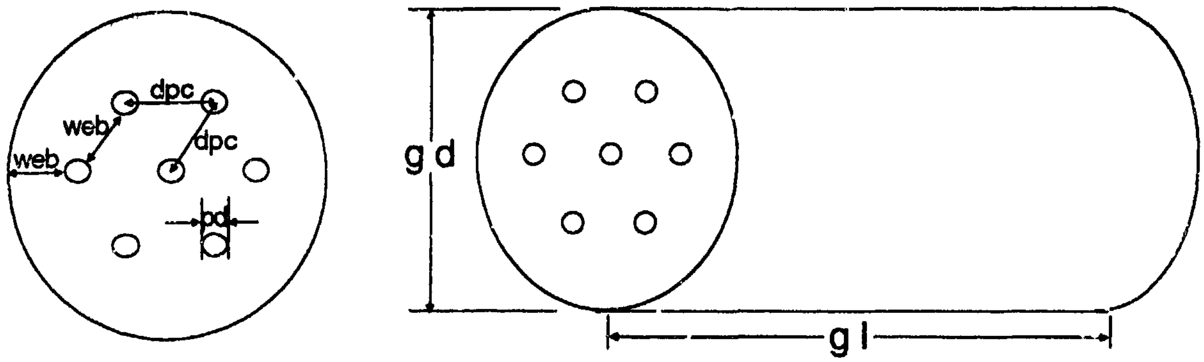

Figure 5-A. 7-Perforated Right Circular Cylindrical Grain.

For: $.5 * web < x < X_2$ (up to where the outer sliver burns out)

$$V_2 = (pi * (gd - 2. * x)^2 - 6. * sqrt3 * d^2 - 4. * pi * (pd + 2. * x)^2$$

$$+ 24. * (a_1 + 2. * a_2)) * (gl - 2. * x)/4.$$

$$S_2 = 2. * V_2/(gl - 2. * x) + (gl - 2. * x) * ((pi - 6. * alpha) * (gd - 2. * x)$$

$$+ 2. * (2. * pi - 3. * phi - 3. * theta) * (pd + 2. * x))$$

For: $x \geq X_2$

$$V_2 = 0.$$

$$S_2 = 0.$$

$$frac = 1.$$

$$ds/dx = 0.$$

where:

$$d = (web + pd)$$

$$dpc = d$$

$$web = (gd - 3. * pd)/4.$$

$$theta = \tan^{-1}(sqrt((pd + 2. * x)^2 - d * d)/d)$$

$$chi = \tan^{-1}(sqrt((gd - 2. * x)^2 - (5. * d - 2. * (pd + 2. * x))^2)$$
$$/(5. * d - 2. * (pd + 2. * x)))$$

$$phi = \tan^{-1}(sqrt((pd + 2. * x)^2 - (3. * d - 2. * (pd + 2. * x))^2)$$
$$/(3. * d - 2. * (pd + 2. * x)))$$

$$X_1 = d/sqrt3 - pd/2.$$

$$X_2 = (14.0 - 3.0 * sqrt3) * d/13.0 - pd/2.$$

$$a_1 = theta/4. * (pd + 2. * x)^2 - d/4. * sqrt((pd + 2. * x)^2 - d * d)$$

$$a_2 = (phi * (pd + 2. * x)^2 - chi * (gd - 2. * x)^2 + 2. * sqrt3 * d$$
$$* sqrt((3. * d - pd - 2. * x) * (3. * d - gd + 2. * x)))/8.$$

$$sqrt3 = \sqrt{3}$$

The equations for a 19-perforated right circular cylindrical grain type (Figure 6-A) with equal webs and perforations, where x is the distance burned, are:

For: $x \leq .5 * web$

$$V_o = pi/4. * gl * (gd * gd - 19. * pd * pd)$$

$$V = pi/4. * (gl - 2. * x) * ((gd - 2. * x)^2 - 19. * (pd + 2. * x)^2)$$

$$frac = 1. - V/V_o$$

$$S = 2. * V/(gl - 2. * x) + pi * (gl - 2. * x) * (gd - 2. * x + 19. * (pd + 2. * x))$$

$$ds/dx = pi * (- 4. * gd + 36. * gl - 76. * pd - 216. * x)$$

For: $x > .5 * web$ (after slivering)

$$V = V_1 + V_2$$

$$frac = 1. - V/V_o$$

$$S = S_1 + S_2$$

$$ds/dx = -S/(X_2 - x) \quad \text{(approximately)}$$

For: $.5 * web < x < X_1$ (up to where the inner sliver burns out)

$$V_1 = 3. * (gl - 2. * x) * (2. * sqrt3 * (web + pd)^2 - pi * (pd + 2. * x)^2 + 24. * a_1)$$

$$S_1 = 2. * V_1/(gl - 2 * x) + 12. * (gl - 2. * x) * (pi - 6. * theta) * (pd + 2. * x)$$

For: $x \geq X_1$

$$V_1 = 0.$$

$$S_1 = 0.$$

For: $.5 * web < x < X_2$ (up to where the outer sliver burns out)

$$V_2 = .25 * (gl - 2. * x) * (pi * (gd - 2. * x)^2 - 7. * pi * (pd + 2. * x)^2$$

$$- 24. * sqrt3 * (web + pd) * (web + pd) + 48. * (a_1 + a_2 + a_3))$$

$$S_2 = 2. * V_2/(gl - 2. * x) + (gl - 2. * x) * ((gd - 2. * x) * (pi - 6. * (xi + delta))$$

$$+ (pd + 2. * x) * (7. * pi - 6. * (2. * theta + chi + phi)))$$

For: $x \geq X_2$

$$V_2 = 0.$$

$$S_2 = 0.$$

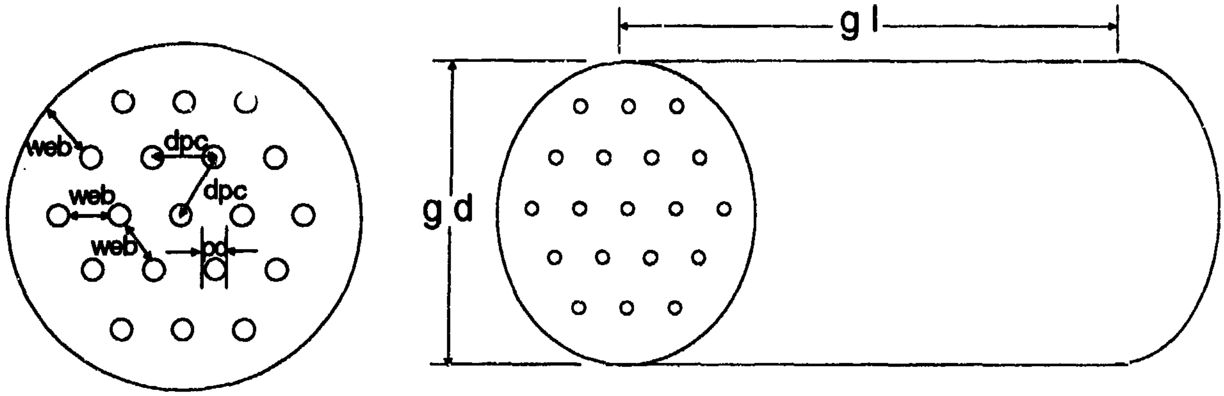

Figure 6-A. <u>19-Perforated Right Circular Cylindrical Grain.</u>

where:

$$web = (gd - 5. * pd)/6.$$

$$xi = \cos^{-1}((13. * gd - 5. * pd - 36. * x)/(12. * (gd - 2. * x)))$$

$$chi = \cos^{-1}((gd - 2. * pd - 6. * x)/(sqrt3 * (pd + 2. * x)))$$

$$delta = \cos^{-1}((2. * gd - pd - 6. * x)/(sqrt3 * (gd - 2. * x)))$$

$$theta = \cos^{-1}((web + pd)/(pd + 2. * x))$$

$$phi = \cos^{-1}((5. * gd - 13. * pd - 36. * x)/(12. * (pd + 2. * x)))$$

$$a_1 = theta/4. * (pd + 2. * x)^2 - (web + pd)/4. * sqrt((pd + 2. * x)^2 - (web + pd) * (web + pd))$$

$$a_2 = .125 * (phi * (pd + 2. * x)^2 - xi * (gd - 2. * x)^2 + 2. * sqrt5 * (web + pd) * sqrt((5. * (web + pd) - pd - 2. * x) * (5. * (web + pd) - gd + 2. * x)))$$

$$a_3 = .125 * (chi * (pd + 2. * x)^2 - delta * (gd - 2. * x)^2 + 2.(sqrt6 * (web + pd) * sqrt(6. * (web + pd) * (pd + 2. * x - (web + pd)) - (pd + 2. * x)^2))$$

$$dbc = web + pd$$

$$X_1 = dbc/sqrt3 - pd/2.$$

$$X_2 = 0.25 * (dbc * (6. - sqrt10) - 2. * pd)$$

$$sqrt3 = \sqrt{3}$$

The equations for a 19-perforation right hexagonal grain type (Figure 7-A) with equal webs and perforations, where x is the distance burned, are:

For: $x \leq .5 * web$

$$V_o = gl/4. * (2. * sqrt3 * (2. * (sqrt3 * (web + pd) + pd/2. + web)^2 -19. * pi * pd^2) - 6. * a * gl$$

$$V = .25 * (gl - 2. * x) * (2. * sqrt3. * (2. * (sqrt3 * (web + pd) + pd/2. + web) - 2. * x)^2 - 19 * pi * (pd + 2. * x)^2 - 6. * a * (gl - 2. * x)$$

$$frac = 1. - V/V_o$$

$$S = 2. * V/(gl - 2. * x) + (gl - 2. * x) * (2. * sqrt3 * (2. * (sqrt3 * (web + pd) + p/2. + web) - 2. * x) + 19. * pi * (pd + 2. * x)) - 12. * a + (gl - 2. * x) * (web - 2. * x + (pd + 2. * x)/2.) * (4. * sqrt3 - 2. * pi)$$

$$ds/dx = -8 . * sqrt3 * (2. * (sqrt3 * (web + pd) + pd/2. + web) - 2. * x) - 76. * pi * (pd + 2. * x) + (gl - 2. * x) * (- 4. * sqrt3 + 38. * pi) + 16. * sqrt3 * (web + pd/2. - x) - 8. * pi * (web + pd/2. - x) + (gl - 2. * x) * (4. * sqrt3 - 2. * pi)$$

For: $x > .5 * web$ (after slivering)

$$V = V_1 + V_2$$

$$frac = 1. - V/V_o$$

$$S = S_1 + S_2$$

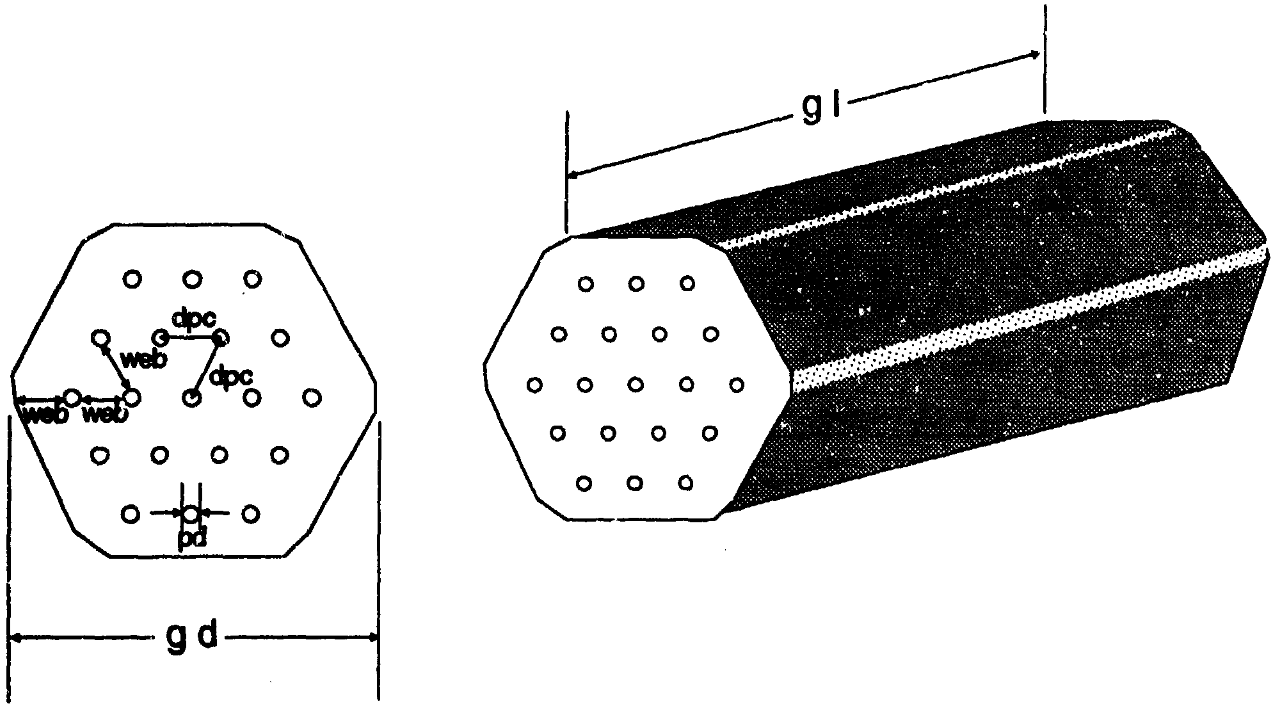

Figure A-7. 19-Perforated Right Hexagonal Grain With Rounded Corners.

$$S = S_1 + S_2$$

$$ds/dx = -S/(X_2 - x) \qquad \text{(approximately)}$$

For: web/2. < x < X_1 (up to where the inner sliver burns out)

$$V_1 = 3. * (gl - 2. * x) * (2. * sqrt3 * (web + pd)^2 - pi * (pd + 2. * x)^2 + 24. * a_1)$$

$$V_2 = 6. * (gl - 2. * x) * (2. * (web + pd)^2 - (web + pd) * (pd + 2. * x) - pi/4.$$
$$* (pd + 2. * x)^2 + 2. * a_1 + 4. * a_2)$$

$$S_1 = 2. * V_1/(gl - 2. * x) + 12. * (gl - 2. * x) * (pi - 6. * theta) * (pd + 2. * x)$$

$$S_2 = 2. * V_2/(gl - 2. * x) + 12. * (gl - 2. * x) * ((web + pd)$$
$$+ (pd + 2. * x) * (pi/2. - omega - theta - sin(omega)))$$

$$V = V_1 + V_2$$

$$S = S_1 + S_2$$

For: $X_1 < x < X_2$ (up to where the outer sliver burns out)

$$V_1 = 0.$$

$$V_2 = 6. * (gl - 2. * x) * (2. * (web + pd)^2 - web + pd * (pd + 2. * x) - pi/4.$$

$$* (pd + 2. * x)^2 + 2. * a_1 + 4. * a_2)$$

$$S_1 = 0.$$

$$S_2 = 2. * V_2/(gl - 2. * x) + 12. * (gl - 2. * x) * ((web + pd)$$

$$+ (pd + 2. * x)) * (pi/2. - omega - theta - sin(omega))$$

$$V = V_1 + V_2$$

$$S = S_1 + S_2$$

For $x \geq X_2$

$$V_2 = 0.$$

$$frac = 1.$$

$$S_2 = 0.$$

$$ds/dx = 0.$$

where:

$$web = (gd - 5. * pd)/6.$$

$$omega = \cos^{-1}(2. * (web + pd)/(pd + 2. * x) - 1)$$

$$theta = \cos^{-1}((web + pd)/(pd + 2. * x))$$

$$a = sqrt3/3. * (web - 2. * x + (pd + 2. * x)/2.)^2 - pi/6. * (web - 2. * x$$

$$+ (pd + 2. * x)/2.)^2$$

$$a_1 = theta/4. * (pd + 2. * x)^2 - (web + pd)/4. * sqrt((pd + 2. * x)^2$$

$$- (web + pd)^2)$$

$$a_2 = .125 * (pd + 2. * x) * ((pd + 2. * x) * (omega + \sin(omega)) - 2. * (web + pd) * \sin(omega))$$

$$dpc = web + pd$$

$$X_1 = dbc/sqrt3 - p/2.$$

$$X_2 = 0.125 * (5. * dbc - 4. * pd)$$

$$sqrt3 = \sqrt{3}$$

The equations for a slotted single-perforated right circular cylindrical grain type (Figure A-8) are:

$$V_o = gl * ((pi - theta) * r_o^2 - (pi - alpha) * r_i^2 - (.5 * sw * r_o * \cos(theta) - .5 * sw * r_i * \cos(alpha)))$$

$$V = (gl - 2. * x) * ((pi - theta) * r_o^2 - (pi - alpha) * r_i^2 - (.5 * (sw + 2. * x) * r_o * \cos(theta) - .5 * (sw + 2. * x) * r_i * \cos(alpha)))$$

$$S_1 = 2. * (gl - 2. * x) * ((pi - alpha) * r_i + r_o * \cos(theta) - r_i * \cos(alpha))$$

$$S_2 = 2. * ((pi - theta) * r_o^2 - (pi - alpha) * r_i^2 - (.5 * (sw + 2. * x) * r_o * \cos(theta) - .5 * (sw + 2. * x) * r_i * \cos(alpha))) \quad \text{(end)}$$

$$S_3 = 2. * (gl - 2. * x) * (pi - theta) * r_o \quad \text{(lateral)}$$

$$S = S_1 + S_2 + S_3$$

$$frac = 1. - V/V_o$$

$$ds/dx_1 = -4. * ((pi - alpha) * r_i + r_o * \cos(theta) - r_i * \cos(alpha)) + 2. * (gl - 2. * x) * ((pi - alpha) + r_i * (- dalpha) + (- \cos(theta)) + r_o * (- \sin(theta)) * dtheta - \cos(alpha) - r_i * (- \sin(alpha)) * dalpha) \quad \text{(perforation)}$$

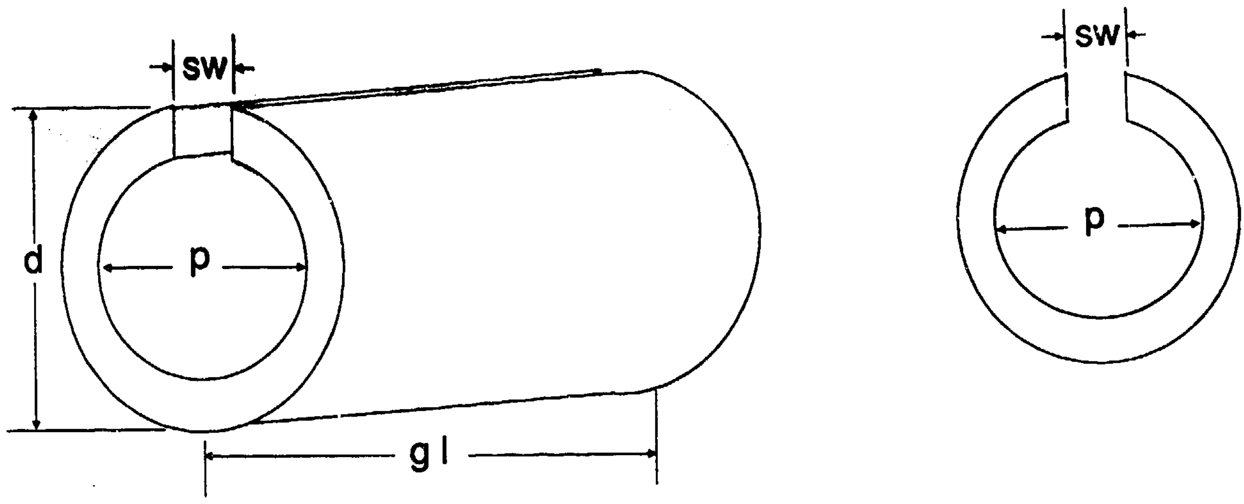

Figure A-8. Slotted Single-Perforated Right Circular Cylindrical Grain.

$$ds/dx_2 = -2. * dtheta * r_o^2 - 4. * (pi - theta) * r_o + 2. * dalpha * r_i^2 - 4. * (pi - alpha) * r_i - 2. * r_o * \cos(theta) + (sw + 2. * x) * \cos(theta) + (sw + 2. * x) * r_o * \sin(theta) * dtheta + 2. * r_i * \cos(alpha) + (sw + 2. * x) * \cos(alpha) - (sw + 2. * x) * r_i * \sin(alpha) * dalpha$$

$$ds/dx_3 = -4. * (pi - theta) * r_o + 2. * (gl - 2. * x) * (- dtheta) * r_o + -2. * (gl - 2. * x) * (pi - theta) \quad \text{(lateral)}$$

$$ds/dx = dx/dx_1 + ds/dx_2 + ds/dx_3$$

For: $x \geq X_2$

$$V_2 = 0.$$

$$frac = 1.$$

$$S_2 = 0.$$

$$ds/dx = 0.$$

where:

$$r_o = (d - 2.*x)/2$$

$$r_i = (p + 2.*x)/2$$

$$\text{theta} = \sin^{-1}((.5*sw + x)/(d/2 - x))$$

$$\text{dtheta} = 2.*(d + sw)/(d - 2.*x)^2/\text{sqrt}(1. - ((sw + 2.*x)/(d - 2.*x))^2)$$

$$\text{alpha} = \sin^{-1}((.5*sw + x)/(p/2. + x))$$

$$\text{dalpha} = 2.*(p - sw)/(p + 2.*x)^2/\text{sqrt}(1. - ((sw + 2.*x)/(p + 2.*x))^2)$$

LIST OF SYMBOLS FOR THE FORM FUNCTION FUNCTIONS

Symbols	Definition	Units
gl	grain length	m
gd	major diameter	m
pd	perforation diameter	m
sw	slot width	m
web	web	m
w	grain width	m
h	grain height	m
x	distance burned	m
X_1	distance burned when inner slivers burns out	m
X_2	distance burned when outer slivers burn out	m
S	surface area of the grain	m^2
S_1	surface area of the inner grain except for the slotted grain which represents the perforated surface area	m^2
S_2	surface area of the outer grain except for the slotted grain which represents the end surface area	m^2
S_3	surface area of the lateral section of a slotted grain	m^2
V	volume of the grain	m^3
V_0	initial volume of the grain	m^3
V_1	volume of the inner sliver	m^3
V_2	volume of the outer sliver	m^3
ds/dx	the rate of change of the surface area with respect to distance	m
ds/dx_1	the rate of change of the surface area for the perforation of a slotted grain with respect to distance	m
ds/dx_2	the rate of change of the surface area for the end of a slotted grain with respect to distance	m
ds/dx_3	the rate of change of the surface area for the lateral of a slotted grain with respect to distance	m

Symbols	Definition	Units
frac	mass fraction	
a	area	m^2
da	the rate of change of the area with respect to distance	m
a_1	area of the inner slivers	m^2
da_1	the rate of change of the area of the inner slivers with respect to distance	m
a_2	area of the outer slivers	m^2
da_2	the rate of change of the area of the outer slivers with respect to distance	m
a_3	area to be removed from the outer sliver of a 19-perforated grain	m^2
da_3	the rate of change of the area to be removed from the outer sliver of a 19-perforated grain with respect to distance	m
r_o	the radius of the grain diameter	m
r_i	the radius of the perforated diameter	m

APPENDIX B:

USER'S MANUAL FOR THE PROGRAMS PT, SURF, AND BR

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The user manual for the PT, SURF, and BR programs consists of a description of the numerical parameters necessary in running the computer codes. The programs are based on the metric system for the numerical parameters and must remain constant throughout the database. Below is the basic database showing the name and location for the variable with an alphabetical designator corresponding to the position at which the data is to appear, that is, from left to right. The data may be separated by blanks or commas, and measurement units, if any, are shown at the right of each input.

Title card - up to 60 characters of the title and identification.

Parameter information and placement:

A B C D E F

	Metric
Record 1:	
A.-Low pressure	MPa
B.-High pressure	MPa
Record 2:	
A.-Heat capacity at constant volume of the propellant gases	cal/kg/k
B.-Heat capacity at constant volume of igniter gases	cal/kg/k
C.-Covolume of propellant	m^3/kg
D.-Covolume of igniter	m^3/kg
Record 3:	
A.-Flame temperature of propellant gases	K
B.-Flame temperature of igniter gases	K
C.-Molecular weight of propellant gases	kg/kg mole
D.-Molecular weight of igniter gases	kg/kg mole

Record 4:

A.-Density of solid propellant	kg/m^3
B.-Density of solid igniter	kg/m^3

Record 5:

A.-Mass of propellant	kg
B.-Mass of igniter	kg
C.-Empty closed bomb volume	m^3

Record 6:

A.-Perforation diameter of the propellant	m
B.-Grain diameter of the propellant	m
C.-Grain length of the propellant	m
D.-Slot width of the propellant	m
E.-Indictor for the form function	

Record 7:

A.-Heat loss up to the start of the calculation	J
B.-Maximum pressure	Pa
C.-Squib pressure	Pa
D.-Print increment	s
E.-Calculated delta time	s

Record 8:

A.-Number of burning rate points

Record 9:

A.-a of aP^n equation	$m/(s\text{-}MPa^n)$
B.-n of aP^n equation	
C.-Upper limit pressure	MPa
A.-a of aP^n equation	$m/(s\text{-}MPa^n)$
B.-n of aP^n equation	
C.-Upper limit pressure	MPa

Below are the input databases for the two case studies. The first five databases are for the single-perforated right circular cylindrical slotted grain, and the other databases are for the 19-perforated right circular cylindrical grain.

```
BASE.IN
0.,388.
250.,300.,.000975437,.00101156
2500.,3000.,22.,23.
1200.,1300.
0.06,.001,.0002
0.0005,.0063,.0127,.0000254,11
0., 394911000.,344738.,.000005,.000005
2
0.001105188 1. 689.476 .001105188 1. 689.476
```

```
CV.IN
0.,388.
224.75,300.,.000975437,.00101156
2500.,3000.,22.,23.
1200.,1300.
0.06,.001,.0002
0.0005,.0063,.0127,.0000254,11
0., 394911000.,344738.,.000005,.000005
2
0.001105188 1. 689.476 .001105188 1. 689.476
```

```
GRGD.IN
0.,388.
250.,300.,.000975437,.00101156
2500.,3000.,22.,23.
1200.,1300.
0.06,.001,.0002
0.0005,.00567,.0127,.0000254,11
0., 394911000.,344738.,.000005,.000005
2
0.001105188 1. 689.476 .001105188 1. 689.476
```

```
GRPD.IN
0.,388.
250.,300.,.000975437,.00101156
2500.,3000.,22.,23.
1200.,1300.
0.06,.001,.0002
0.00045,.0063,.0127,.0000254,11
0., 394911000.,344738.,.000005,.000005
2
0.001105188 1. 689.476 .001105188 1. 689.476
```

```
DEN.IN
0.,388.
250.,300.,.000975437,.00101156
2500.,3000.,22.,23.
1080.,1300.
0.06,.001,.0002
0.0005,.0063,.0127,.0000254,11
0., 394911000.,344738.,.000005,.000005
2
0.001105188 1. 689.476 .001105188 1. 689.476
```

```
BASE1.IN
0.,388.
250.,300.,.000975437,.00101156
2500.,3000.,22.,23.
1200.,1300.
0.06,.001,.0002
0.0005,.0063,.0127,.0000254,19
0., 394911000.,344738.,.000005,.000005
2
0.001105188 1. 689.476 .001105188 1. 689.476
```

```
CV1.IN
0.,388.
310.,300.,.000975437,.00101156
2500.,3000.,22.,23.
1200.,1300.
0.06,.001,.0002
0.0005,.0063,.0127,.0000254,19
0., 394911000.,344738.,.000005,.000005
2
0.001105188 1. 689.476 .001105188 1. 689.476
```

GRGD1.IN
0.,388.
250.,300.,.000975437,.00101156
2500.,3000.,22.,23.
1200.,1300.
0.06,.001,.0002
0.0005,.00567,.0127,.0000254,19
0., 394911000.,344738.,.000005,.000005
2
0.001105188 1. 689.476 .001105188 1. 689.476

GRPD1.IN
0.,388.
250.,300.,.000975437,.00101156
2500.,3000.,22.,23.
1200.,1300.
0.06,.001,.0002
0.00045,.0063,.0127,.0000254,19
0., 394911000.,344738.,.000005,.000005
2
0.001105188 1. 689.476 .001105188 1. 689.476

DEN1.IN
0.,388.
250.,300.,.000975437,.00101156
2500.,3000.,22.,23.
1080.,1300.
0.06,.001,.0002
0.0005,.0063,.0127,.0000254,19
0., 394911000.,344738.,.000005,.000005
2
0.001105188 1. 689.476 .001105188 1. 689.476

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APPENDIX C:

PROGRAM LISTING FOR PT

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```
C 'PT - REDUCTION OF CLOSED BOMB DATA/PRESSURE-TIME'
C
      PROGRAM PT
C     /PT WITH METRIC UNITS
C
      CHARACTER OUTFIL*10, ALABEL*40
      CHARACTER BDFILE*10, PTFILE*10
      CHARACTER*40 STRIN
      CHARACTER*20 STRIN2
      CHARACTER*35 STRIN3
      DIMENSION HP(5000),HT(5000),BETA(10),ALPHA(10),PRESBR(10)
      REAL MASSP,MASSI,MASAIR,K8
      WRITE(*,16)
16    FORMAT(' INPUT NAME OF DATA FILE TO BE USED AS INPUT ')
      READ(*,10)BDFILE
10    FORMAT(A10)
      OPEN(UNIT=3,FILE=BDFILE,STATUS='OLD')
      REWIND 3
      WRITE(*,25)
25    FORMAT(' INPUT NAME OF OUTPUT FILE ')
      READ(*,10)OUTFIL
      OPEN(UNIT=5,FILE=OUTFIL)
      OPEN(UNIT=4,FILE='SCRATCH')
      WRITE(*,26)
26    FORMAT( ' INPUT NAME OF P-T FILE')
      READ(*,10)PTFILE
      OPEN(UNIT=6,FILE=PTFILE)
50    READ(3,5) ALABEL
5     FORMAT(A40)
      WRITE(5,401) ALABEL
401   FORMAT(1H ,'OUTPUT FROM PT',/1X,A40)
C
C     READ AND WRITE PRESSURE RANGE THAT BURNING RATE
C     VERSUS PRESSURE WILL BE FIT TO INITALLY (BR=A*P**N)
C
      READ(3,*)PLOW,PHIGH
      WRITE(5,1040) PLOW,PHIGH
1040  FORMAT(/,1X,'LOW PRES VALUE MPA',E12.6,/,1X,
     1 ' HIGH PRES VALUE MPA',E12.6)
C     READ AND WRITE
C     CVPV,CVIV... HEAT CAPACITY AT CONSTANT VOLUME PROP, IGN CAL/KG/K
C     COVPV, COVIV... COVOLUME PROP,IGN    M3/KG
C
      READ(3,*)CVPV,CVIV,COVPV,COVIV
      WRITE(5,470)CVPV,CVIV,COVPV,COVIV
470   FORMAT(' CV PROP    CV IGN    COVOLUME PROP    COVOLUME IGN',/
     1 ' CAL/KG/K  CAL/KG/K        M3/KG               M3/KG',/
     2 F9.3,1X,F9.3,3X,F9.5,4X,F14.5)
      CVPV=CVPV*4.184
      CVIV=CVIV*4.184
      CVA=400.*4.184
C     READ AND WRITE:
C     FTPV,FTIV... FLAME TEMP PROP,IGN (K)
C     RHPV,RHIV... MOL WT PROP,IGN CHANGED INTO R/MW
      READ  (3,*)FTPV,FTIV,RHPV,RHIV
```

```
      WRITE(5,471)FTPV,FTIV,RHPV,RHIV
471   FORMAT(1X,'FLAME TEMP PROP    FLAME TEMP IGN    MOL WT PROP'
     1'   MOL WT IGN'/
     2 '          K                   K                   K',
     3'           K'/
     4 4X,F7.1,4X,F14.1,1X,F14.2,3X,F11.2)
C
C     CHANGE MOL WT INTO UNIVERSAL GAS CONSTANT/MOL WT
C     TO MAKE MATHEMATICS EASIER
C
      RHPV=8315./RHPV
      RHIV=8315./RHIV
C
C     READ AND WRITE:
C     DENPRO,DENIGN... DENSITY OF PROP,IGN (KG/M3)
C
      READ(3,*) DENPRO, DENIGN
C
C     READ AND WRITE:
C     MASSP,MASSI... MASS OF PROP,IGN (KG)
C     VOLBOM............. VOLUME OF BOMB (M3)
C
      READ(3,*)MASSP,MASSI,VOLBOM
435   WRITE(5,130)MASSP,MASSI,DENPRO,DENIGN,VOLBOM
130   FORMAT(1H ,'MASS PROP KG',F6.4,28X,'MASS IGN KG' ,F6.4,
     1  /,' DEN PROP KG/M3 ',F8.2,23X,'DEN IGN KG/M3',F8.2/
     2  ' VOL BOMB M3',E12.6)
C
C     READ AND WRITE:
C     PERFDP,GRDP... PERF DIAMETER OF PROP,GRAIN DIAMETER PROP (M)
C     GLP,SW... GRAIN LENGTH PROP (M),SLOT WIDTH (M)
C     IFF... INDICATOR FOR FORM FUNCTIONS (0=CORD, 1=1 PERF,
C     7=7 PERF,19=19 PER CY,15=19 PERF HEX,11=SLOTTED GRAIN, 2=SPHERICAL,
C     12=SLAB)
C
      READ(3,*)PERFDP,GRDP,GIP,SW,IFF
      WRITE(5,473)PERFDP,GRDP,GLP,SW,IFF
473   FORMAT('PERF DIA ',
     1  '   GRAIN DIA  GRAIN LENGTH  SLOT WIDTH  '
     2  ,' INDICATOR FOR FORM FUNCTION ',/ '    M', 11X, 'M'
     3  ,11X,'M',13X,'M'/F8.6, F10.6, F13.6,4X,F11.8,13X, I3)
C
C     READ AND WRITE:
C     HTLOSI... INITIAL HEAT LOSS (J)
C     PMAX,SQUIBP........ ACTUAL MAXIMUM PRESSURE,SQUIB PRESSURE (PSI)
C     PRTDT... PRINT TIME STEP (SEC)
C
      READ(3,*)HTLOSI,PMAX,SQUIBP,PRTDT,CALDT
      WRITE(5,190)HTLOSI,PMAX,SQUIBP, PRTDT,CALDT
190   FORMAT(1X,'INITIAL HEAT LOSS J',E12.6,16X,'MAX PRESSURE PA',E12.6/
     1  ' SQUIB PRESSURE PA',E12.6,13X, 'PRINT INCREMENT S', E12.6,/
     2  ' CALCULATION  DELTA  TIME  S',E12.6)
      READ(3,*)NBRP
      READ(3,*) (BETA(I),ALPHA(I),PRESBR(I),I=1,NBRP)
      WRITE(5,194)NBRP
      WRITE(5,195) (BETA(I),ALPHA(I),PRESBR(I),I=1,NBRP)
```

```
194   FORMAT(1X,'NUMBER OF BURNING RATE POINTS',I3/
     1  1X,'COEFFICIENT M/(S-MPA^EXP)    EXPONENT     PRESSURE MPA ')
195   FORMAT(1X,G18.6,12X,G11.6,2X,G11.6)
C
C     COVOLUME OF AIR
C
      COVAIR = 30.*16.387/453.6*.001
C
C     MASS OF AIR IN CLOSED BOMB
C
      PA=101353.
      MASAIR = PA*(VOLBOM-MASSP/DENPRO-MASSI/DENIGN)/(300.*8315./29.)
      P = SQUIBP
C
C     INITIAL FREE VOLUME
C
      VOL=VOLBOM-MASSI/DENIGN-MASSP/DENPRO-MASAIR*COVAIR
C
C     CALCULATE THE EXTRA MASS OF IGNITER THAT WOULD NEED TO BE
C     BURNED TO GIVE THE SQUIB PRESSURE AND ADD TO MASS OF IGNITER
C
C     THIS IS AN ESTIMATE TO ACCOUNT FOR THE PRESENCE OF THE
C     INITIATOR/SQUIB USED TO SET OFF THE IGNITER
C
      AA11=RHIV*CVIV*FTIV
      BB11=300.*RHIV*MASAIR*CVA+(8315./29.)*MASAIR*CVIV*FTIV-SQUIBP*
     1 VOL*CVIV
      CC11=300.*(8315./29)*CVA*MASAIR**2-SQUIBP*VOL*CVA*MASAIR
      BB1=BB11/AA11
      CC1=CC11/AA11
      EXIGN=(-BB1+SQRT(BB1**2-4.*CC1))/2.0
      MASSI = MASSI+EXIGN
C
C     CALCULATE THE THEORETICAL MAXIMUM PRESSURE FROM BURNING
C     UPDATED MASS OF IGNITER AND PROPELLANT, WITH NO HEAT LOSS
C
      TEMPG=MASSP*CVPV*FTPV+MASSI*CVIV*FTIV+CVA*MASAIR*300.
      TEMPG=TEMPG/(MASSP*CVPV+MASSI*CVIV+MASAIR*CVA)
      VOL=VOLBOM-MASSP*COVPV-MASSI*COVIV-MASAIR*COVAIR
      RHG=MASAIR*8315./29.+MASSI*RHIV+MASSP*RHPV
      P=RHG*TEMPG/VOL
      WRITE(5,187)P
 187  FORMAT(1X,'THEORETICAL MAXIMUM PRESSURE  PA',G12.6)
C
C     CALCULATE ENERGY LOSS (J) REQUIRED TO GET FROM
C     THEORETICAL MAXIMUM PRESSURE DOWN TO ACTUAL PMAX
C
      RHG=RHG/(MASSP+MASSI+MASAIR)
      CV=(CVPV*MASSP+CVIV*MASSI+CVA*MASAIR)/(MASSP+MASSI+MASAIR)
      HEATLS=CV*VOL*(P-PMAX)/RHG

C     CALCULATE AND PRINT K8 (ENERGY LOST PER PSI IN A LINEAR
C     MANNER (J/PA)) SIMPLE HEAT LOSS ASSUMPTION
C
      K8=(HEATLS-HTLOSI)/(PMAX)
      WRITE(5,30)K8
30    FORMAT(/,4X,'HEAT LOSS FACTOR =',G12.6,' J/PA',/)
      TIME = 0.0
```

```
      FRACI=1.0
      PIGN=0.
      HTLOLD=0.
C
C     CALCULATE PRESSURE FROM BURNING ALL OF THE IGNITER AND
C     SET SWITCHES FOR IGNITER HAVING ALL BEEN BURNT
C
      ITER=0
426   PIGNO=PIGN
      ITER=ITER + 1
      VOL = VOLBOM-MASSP/DENPRO-MASAIR*COVAIR-MASSI*COVIV
      RHG=MASAIR*8315./29. + MASSI*RHIV
      TEMPG=(MASSI*CVIV*FTIV+CVA*MASAIR*300.-HTLOSI-HTLOLD)/
     1 (MASSI*CVIV+MASAIR*CVA)
      P = RHG*TEMPG/VOL
      IGNBSW=0
      PIGN=P
      HTLOLD=PIGN*K8
      IF(ITER.GT.20) GO TO 427
      IF(ABS(PIGN-PIGNO).LT.0.00001*PIGN)GO TO 427
      GO TO 426
427   WRITE(5,422)PIGN
422   FORMAT(1X,' IGNITION PRESSURE IS ',F10.2,' PA')
      WRITE(5,423)
423   FORMAT(1X,'   BURN RATE',8X,'PRESSURE',8X,'TIME'
     1  ,8X,'DIST BURN',8X,'MASS PROP'/7X,'M/S',14X,
     2  'PA',11X,'MSEC',12X,'M',16X,'KG')
C
C     INITIALIZE CALL TO FORM FUNCTION
C
519   CALL FORMFN(PERFDP,GRDP,GLP,SW,IFF,0.0,FRACP,VOL2,SURFP,DSDX)
      SURFP0=SURFP
C
C     INITIALIZE VARIABLES
C
      HTLOSS=0.
      DXO=0.
      TMPO=0.
      TMASPO=0.0
      PRTT=0.
      DT1=CALDT
      PIT=0.
      DHDT=0.
      POLD=0.
      BD=0.
      PNEW=0.
      TXP=0.0
      MUG1=0
      P0=0.
      TIMEPR=0.0
      TIME=0.0
      TIMEO=TIME
      TMASI=MASSI
      BDO=0.
193   P1=P
      DO 196 I=1,NBRP
      IF(P*1.E-6.GT.PRESBR(I))GO TO 196
      GO TO 197
```

```
196   CONTINUE
      I=NBRP
197   CONTINUE
      POLD=P
      DXDT=BETA(I)*(P*1.E-6)**ALPHA(I)
      DX=DXDT*DT1
      BD=BDO+DX
      CALL FORMFN(PERFDP,GRDP,GLP,SW,IFF,BD,FRACP,VOL2,SURFP,DSDX)
      PROPM=FRACP*MASSP
      DHDT=K8*(P-P1)
      HTLOSS=HTLOLD+DHDT+HTLOSI
      TGAS=(-HTLOSS+TMASI*CVIV*FTIV+MASAIR*CVA*300.+PROPM*CVPV*FTPV)/
     1  (TMASI*CVIV+MASAIR*CVA+PROPM*CVPV)
      RHAT=TMASI*RHIV+MASAIR*8315./29.+PROPM*RHPV
      VOL=VOLBOM-MASSP/DENPRO+PROPM/DENPRO-TMASI*COVIV-MASAIR*COVAIR
     1  -PROPM*COVPV
      P=RHAT*TGAS/VOL
      IF(ABS(POLD-P).LT.0.00001*P)GO TO 428
      GO TO 197
428   TIME=TIME+DT1
      BDO=BDO+DX
      WRITE(4,*)P,TIME
      MUG1=MUG1+1
      HP(MUG1)=P
      HT(MUG1)=TIME
      TIMEMS=TIME*1000.
      HTLOLD=HTLOLD+DHDT
      WRITE(5,424)DXDT,P,TIMEMS,BD,PROPM
424   FORMAT(1X,F11.5,F17.2,F11.2,F17.6,F16.5)
      IF(P.GT..999*PMAX) GO TO 198
      GO TO 193
198   REWIND 4
      REWIND 6
      MUG2=MUG1+2
      WRITE(6,*)DT1
      WRITE(6,*)MUG2
      WRITE(6,*)PMAX
      WRITE(6,*)P0
      WRITE(6,*)PIGN
      DO 199 I=1, MUG1
      READ(4,*)P,TIME
      WRITE(6,*)P
199   CONTINUE
C     STRIN='          PT PLOT OF '//BDFILE
C     STRIN2='TIME (SEC)'
C     STRIN3='PRESSURE (PA)'
C     CALL PLOT(HT,HP,MUG1,STRIN2,STRIN3,STRIN)
      END
```

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APPENDIX D:

PROGRAM LISTING FOR SURF

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```
C     'SURF - REDUCTION OF CLOSED BOMB DATA/SURFACE'
C
      PROGRAM SURF
C     /SURF WITH METRIC UNITS
C
      CHARACTER OUTFIL*10, ALABEL*40
      CHARACTER BDFILE*10, PTFILE*10
      CHARACTER*40 STRIN
      CHARACTER*20 STRIN2
      CHARACTER*35 STRIN3
      DIMENSION PP(7), SAPP(7),SAPPF(7)
      DIMENSION HSURFF(5000),HDIST(5000),BETA(10)
      DIMENSION ALPHA(10),PRESBR(10)
      REAL MASSP,MASSI,MASAIR,K8
      DO 9 I=1,7
    9 PP(I)=50.E6*I
      WRITE(*,16)
16    FORMAT(' INPUT NAME OF DATA FILE TO BE USED AS INPUT ')
      READ(*,10)BDFILE
10    FORMAT(A10)
      OPEN(UNIT=3,FILE=BDFILE,STATUS='OLD')
      REWIND 3
      WRITE(*,25)
25    FORMAT(' INPUT NAME OF OUTPUT FILE ')
      READ(*,10)OUTFIL
      OPEN(UNIT=5,FILE=OUTFIL)
      OPEN(UNIT=4,FILE='SCRATCH')
      WRITE(*,26)
26    FORMAT( ' INPUT NAME OF P-T FILE')
      READ(*,10)PTFILE
      OPEN(UNIT=6,FILE=PTFILE,STATUS='OLD')
50    READ(3,5) ALABEL
5     FORMAT(A20)
      WRITE(5,401) ALABEL
401   FORMAT(1H ,'OUTPUT FROM SURF',/1X,A40)
C
C     READ AND WRITE PRESSURE RANGE THAT BURNING RATE
C     VERSUS PRESSURE WILL BE FIT TO INITALLY (BR=A*P**N)
C
      READ(3,*)PLOW,PHIGH
      WRITE(5,1040) PHIGH,PLOW
1040  FORMAT(/,1X,'HIGH PRES VALUE MPA',E12.6,/,1X,
     1 ' LOW PRES VALUE MPA',E12.6)
C     READ AND WRITE
C     CVPV,CVIV... HEAT CAPACITY AT CONSTANT VOLUME PROP, IGN CAL/KG/K
C     COVPV, COVIV... COVOLUME PROP,IGN    M3/KG
C
      READ(3,*)CVPV,CVIV,COVPV,COVIV
      WRITE(5,470)CVPV,CVIV,COVPV,COVIV
470   FORMAT(' CV PROP    CV IGN    COVOLUME PROP    COVOLUME IGN',/
     1 ' CAL/KG/K  CAL/KG/K       M3/KG              M3/KG',/
     2 F9.3,1X,F9.3,3X,F9.5,4X,F14.5)
      CVPV=CVPV*4.184
      CVIV=CVIV*4.184
      CVA=400.*4.184
C     READ AND WRITE:
C     FTPV,FTIV... FLAME TEMP PROP,IGN (K)
```

```
C     RHPV,RHIV... MOL WT PROP,IGN CHANGED INTO R/MW
C
      READ  (3,*)FTPV,FTIV,RHPV,RHIV
      WRITE(5,471)FTPV,FTIV,RHPV,RHIV
471   FORMAT(1X,'FLAME TEMP PROP   FLAME TEMP IGN   MOL WT PROP'
     1'   MOL WT IGN'/
     2 '          K                 K                 K',
     3 '          K'/
     4  4X,F7.1,4X,F14.1,1X,F14.2,3X,F10.2)
C
C     CHANGE MOL WT INTO UNIVERSAL GAS CONSTANT/MOL WT
C     TO MAKE MATHEMATICS EASIER
C
      RHPV=8315./RHPV
      RHIV=8315./RHIV
C
C     READ AND WRITE:
C     DENPRO,DENIGN... DENSITY OF PROP,IGN (KG/M3)
C
      READ(3,*) DENPRO, DENIGN
C
C     READ AND WRITE:
C     MASSP,MASSI... MASS OF PROP,IGN (KG)
C     VOLBOM............. VOLUME OF BOMB (M3)
C
      READ(3,*)MASSP,MASSI,VOLBOM
435   WRITE(5,130)MASSP,MASSI,DENPRO,DENIGN,VOLBOM
130   FORMAT(1H ,'MASS PROP KG',F6.4,28X,'MASS IGN KG',F6.4,
     1  /,' DEN PROP KG/M3',F8.2,23X,'DEN IGN KG/M3',F8.2/
     2  ' VOL BOMB M3',E12.6)
C
C     READ AND WRITE:
C     PERFDP,GRDP... PERF DIAMETER OF PROP,GRAIN DIAMETER PROP (M)
C     GLP,SW... GRAIN LENGTH PROP(M),SLOT WIDTH(M)
C     IFF... INDICATOR FOR FORM FUNCTIONS (0=CORD,1=1 PERF,7=7 PERF,
C     19=19 PERF CY,15=19 PERF HEX,11=SLOTTED GRAIN,2=SPHERICAL,12=SLAB)
C
      READ(3,*)PERFDP,GRDP,GLP,SW,IFF
      WRITE(5,473)PERFDP,GRDP,GLP,SW,IFF
473   FORMAT('PERF DIA ',
     1  '  GRAIN DIA  GRAIN LENGTH  SLOT WIDTH  '
     2  ,' INDICATOR FOR FORM FUNCTION ',/ '    M', 11X, 'M'
     3  ,12X,'M',13X,'M'/F8.6, F10.6,F13.6,4X, F11.8,13X,I3)
C
C     READ AND WRITE:
C     HTLOSI... INITIAL HEAT LOSS (J)
C     PMAX,SQUIBP........ ACTUAL MAXIMUM PRESSURE,SQUIB PRESSURE (PA)
C     PRTDT... PRINT TIME STEP (SEC)
C
      READ(3,*)HTLOSI,PMAX,SQUIBP,PRTDT
C
C     READ FIRST NUMBER -- PDT IN SECONDS
C
      READ(6,*)PDT
      READ(6,*)NPT
      READ(6,*)PMAXH
      IF (PMAX.LE.0)PMAX = PMAXH
```

```
      WRITE(5,190)HTLOSI,PMAX,SQUIBP, PRTDT,PDT
190   FORMAT(1X,'INITIAL HEAT LOSS J',E12.6,16X,'MAX PRESSURE PA',E12.6/
     1 ' SQUIB PRESSURE PA',E12.6,13X, 'PRINT INCREMENT S', E12.6/
     3 ' CALCULATION DELTA TIME S',E12.6)
      READ(3,*)NBRP
      READ(3,*) (BETA(I),ALPHA(I),PRESBR(I),I=1,NBRP)
      WRITE(5,194)NBRP
      WRITE(5,195) (BETA(I),ALPHA(I),PRESBR(I),I=1,NBRP)
194   FORMAT(1X,'NUMBER OF BURNING RATE POINTS',I3/
     1 1X,'COEFFICIENT M/(S-MPA^EXP)   EXPONENT     PRESSURE MPA')
195   FORMAT(1X,G18.6,11X,G11.6,1X,G11.6)
C
C     COVOLUME OF AIR
C
      COVAIR = 30.*16.387/453.6*.001
C
C     MASS OF AIR IN CLOSED BOMB
C
      PA=101353.
      MASAIR = PA*(VOLBOM-MASSP/DENPRO-MASSI/DENIGN)/(300.*8315./29.)
      P = SQUIBP
C
C     INITIAL FREE VOLUME
C
      VOL=VOLBOM-MASSI/DENIGN-MASSP/DENPRO-MASAIR*COVAIR
C
C     CALCULATE THE EXTRA MASS OF IGNITER THAT WOULD NEED TO BE
C     BURNED TO GIVE THE SQUIB PRESSURE AND ADD TO MASS OF IGNITER
C
C     THIS IS AN ESTIMATE TO ACCOUNT FOR THE PRESENCE OF THE
C     INITIATOR/SQUIB USED TO SET OFF THE IGNITER
C
      AA11=RHIV*CVIV*FTIV
      BB11=300.*RHIV*MASAIR*CVA+(8315./29)*MASAIR*CVIV*FTIV-SQUIBP*
     1 VOL*CVIV
      CC11=300.*(8315./29)*CVA*MASAIR**2-SQUIBP*VOL*CVA*MASAIR
      BB1=BB11/AA11
      CC1=CC11/AA11
      EXIGN=(-BB1+SQRT(BB1**2-4.*CC1))/2.0
      MASSI = MASSI+EXIGN
C
C     CALCULATE THE THEORETICAL MAXIMUM PRESSURE FROM BURNING
C     UPDATED MASS OF IGNITER AND PROPELLANT, WITH NO HEAT LOSS
C
      TEMPG=MASSP*CVPV*FTPV+MASSI*CVIV*FTIV+CVA*MASAIR*300.
      TEMPG=TEMPG/(MASSP*CVPV+MASSI*CVIV+MASAIR*CVA)
      VOL=VOLBOM-MASSP*COVPV-MASSI*COVIV-MASAIR*COVAIR
      RHG=MASAIR*8315./29.+MASSI*RHIV+MASSP*RHPV
      P=RHG*TEMPG/VOL
      WRITE(5,187)P
  187 FORMAT(1X,'THEORETICAL MAXIMUM PRESSURE PA',G12.6)
C
C     CALCULATE ENERGY LOSS (J) REQUIRED TO GET FROM
C     THEORETICAL MAXIMUM PRESSURE DOWN TO ACTUAL PMAX
```

```
C
      RHG=RHG/(MASSP+MASSI+MASAIR)
      CV=(CVPV*MASSP+CVIV*MASSI+CVA*MASAIR)/(MASSP+MASSI+MASAIR)
      HEATLS=CV*VOL*(P-PMAX)/RHG
C
C     CALCULATE AND PRINT K8 (ENERGY LOST PER PA IN A LINEAR
C     MANNER (J/PA)) SIMPLE HEAT LOSS ASSUMPTION
C
      K8=(HEATLS-HTLOSI)/(PMAX)
      WRITE(5,30)K8
30    FORMAT(/,4X,'HEAT LOSS FACTOR =',G12.6,' J/PA',/)
      TIME = 0.0
      FRACI=1.0
      PIGN=0.
      HTLOLD=0.
C
C     CALCULATE PRESSURE FROM BURNING ALL OF THE IGNITER AND
C     SET SWITCHES FOR IGNITER HAVING ALL BEEN BURNT
C
      ITER=0
426   PIGNO=PIGN
      ITER=ITER + 1
      VOL = VOLBOM-MASSP/DENPRO-MASAIR*COVAIR-MASSI*COVIV
      RHG=MASAIR*8315./29. + MASSI*RHIV
      TEMPG=(MASSI*CVIV*FTIV+CVA*MASAIR*300.-HTLOSI-HTLOLD)/
     1 (MASSI*CVIV+MASAIR*CVA)
      P = RHG*TEMPG/VOL
      IGNBSW=0
      PIGN=P
      HTLOLD=PIGN*K8
      IF(ITER.GT.20) GO TO 427
      IF(ABS(PIGN-PIGNO).LT..00001)GO TO 427
      GO TO 426
427   WRITE(5,422)PIGN
422   FORMAT(1X,' IGNITION PRESSURE IS ',F10.2,' PA')
C
C     INITIALIZE CALL TO FORM FUNCTION
C
519   CALL FORMFN(PERFDP,GRDP,GLP,SW,IFF,0.0,FRACP,VOL2,SURFP,DSDX)
      SURFP0=SURFP
      TNG=MASSP/(DENPRO*VOL2)
C
C     INITIALIZE VARIABLES
C
      HTLOSS=0.
      HTLOLD=0.
      DXO=0.
      TMPO=0.
      TMASPO=0.0
      PRTT=0.
      DT1=0.
      PIT=0.
      DHDT=0.
      POLD=0.
      BD=0.
      PNEW=0.
      TXP=0.0
      TMASP=0.0
```

```
      MUG1=0
      P1=P
      TIMEPR=0.0
      STMASP=-0.000001*MASSP
      A1=0.0
      TIME=0.0
      MUG2=1
      MUG3=0
      TIMEO=TIME
      KHOLD=0
      BRMAX=0.0
      PRMAX=0.0
      DX=0.0000001
      READ(6,*)P
      TIME=0
      P1 = PIGN
      PRTT = TIME
      TIMEO = TIME
      OLDM=0.0
      I2=1
      SURFPO=0.0
      SURFPP=0.0
C
C
C     READ P,T POINTS UNTIL PRESSURE IS GREATER THAN
C     ALL-BURNT IGNITER PRESSURE
C
303   READ(6,*)P
      MUG2=MUG2+1
      TIME=TIME+PDT
      IF(P.GT.PIGN+.000001*PIGN) GO TO 3332
      PRTT = TIME
      TIMEO = TIME
      GO TO 303
C
C     READ P,T POINT UNTIL PRESSURE IS GREATER THAN ZERO OR
C     GREATER THAN THE LAST USED PRESSURE POINT
202   READ(6,*)P
      MUG2=MUG2+1
      TIME=TIME+PDT
3332  DT1=TIME-TIMEO
      IF(P.LT.0.0) GO TO 202
333   IF(P.LE.P1+1.) GO TO 202
C
C     MASS OF IGNITER BURNT (TMASI) (IN THIS CASE ALWAYS 100%)

208      TMASI=MASSI*FRACI
C
C     CALCULATE HEAT LOSS UP TO NOW
C
      DHDT=K8*(P-P1)
      HTLOSS=HTLOLD+DHDT+HTLOSI
C
C     CALCULATE THE TOTAL MASS OF PROPELLANT BURNT UP TO
C     NOW (TMASP), FROM PRESSURE AND COVOLUME EQUATION OF STATE
C     WITH THERMODYNAMIC DATA
C
      B1=P*(1./DENPRO-COVPV)*CVPV-RHPV*CVPV*FTPV
```

```
      B2=(TMASI*CVIV+MASAIR*CVA)*P*(1./DENPRO-COVPV)
     1 +CVPV*P*(VOLBOM-MASSP/DENPRO-MASSI/DENIGN+TMASI*(1./DENIGN-COVIV)
     2 -MASAIR*COVAIR)
      B2=B2-CVPV*FTPV*(TMASI*RHIV+MASAIR*8315./29.)
     1 -RHPV*(TMASI*CVIV*FTIV+MASAIR*CVA*300.-HTLOSS)
      B3=(TMASI*(1./DENIGN-COVIV)+VOLBOM-MASSP/DENPRO-MASSI/DENIGN
     1 -MASAIR*COVAIR)*P*(TMASI*CVIV+MASAIR*CVA)
      B3=B3-(TMASI*RHIV+MASAIR*8315./29.)*(TMASI*CVIV*FTIV+MASAIR*.4*
     1 300.-HTLOSS)
      TMASP=(-B2-SQRT(B2*B2-4.*B1*B3))/2./B1
C
C     PRINT OUT PROPELLANT IGNITION (IN THIS CASE IT WILL BE
C     ACCESSED ONLY ON FIRST PRESSURE POINT GREATER THAN
C     PRESSURE FROM BURNING THE IGNITER)
C
220   FORMAT(' PROPELLENT IGNITION AT TIME =',F7.5,' S AND',
     1  ' PRESSURE = ',F12.4, ' PA'/)
240   FORMAT(1X,8HPRESSURE,6X,4HTIME,3X,'DIST BURN',2X,
     1  9HMASS PROP,5X,'FORM SURFACE',5X,'CALC SURFACE')
241   IF(IGNBSW.NE.0)GO TO 529
      WRITE(5,220) TIME,P
      WRITE(5,240)
      WRITE(5,2401)
2401  FORMAT(4X,'PA',10X,'SEC',7X,'M',10X,'KG',12X,
     1 'M**2',13X,'M**2'/)
      IGNBSW=1
C
C     CHECK IF MASS OF PROPELLANT BURNED IS LESS THAN ZERO
C     IF IT IS TRY NEXT HIGHER PRESSURE
C
529   IF(TMASP.LT.0.0) WRITE(5,15) TMASP,TMASI
      IF(TMASP.LT.0.0) GO TO 202
15    FORMAT(1X,'TMASP',E12.5,' TMASI',E12.5)
      DO 196 I=1,NBRP
      IF(P*1.E-6.GT.PRESBR(I))GO TO 196
      GO TO 197
196   CONTINUE
      I=NBRP
197   DXDT=BETA(I)*(P*1.E-6)**ALPHA(I)
      DX=DXDT*DT1
      BD=BD+DX
      CALL FORMFN(PERFDP,GRDP,GLP,SW,IFF,BD,FRACP,VOL2,SURFP,DSDX)
      IF(SURFP.LE.0.0)GO TO 1202
      DMDT=(TMASP-OLDM)/DT1
      OLDM=TMASP
      SURFP1=DMDT/DENPRO/DXDT
      SURFP1=SURFP1/TNG
      MUG3=MUG3+1
      IF(I2.GT.7) GO TO 6346
      IF(P.GE.PP(I2).AND.P1.LT.PP(I2)) THEN
      SAPPF(I2)=SURFPP + (SURFP-SURFPP)/(P-P1)*(PP(I2)-P1)
      SAPP(I2)=SURFPO + (SURFP1-SURFPO)/(P-P1)*(PP(I2)-P1)
      I2=I2 + 1
      ENDIF
 6346 CONTINUE
      IF (MUG3.LE.2) GO TO 198
      MUG1=MUG1+1
```

```
      HSURFF(MUG1)=(SURFP1-SURFP)/SURFP0
      HDIST(MUG1)=BD
  198 TIMEO=TIME
      HTLOLD=HTLOLD+DHDT
      P1=P
      SURFPP=SURFP
      SURFPO=SURFP1
      TIMEMS = TIME*1000.
      IF(TIME.LT.PRTT-.00001) GO TO 1041
      WRITE(5,230)P,TIMEMS,BD,TMASP,SURFP,SURFP1
      PRTT=PRTT+PRTDT
1041  CONTINUE
230   FORMAT(1X,E11.5,3X,F7.3,E10.4,1X,E11.5,5X,E11.5,5X,E11.5)
      IF(P.GT.PMAX-.9999.OR.FRACP.GE..99999) GO TO 1202
      IF(MUG2.EQ.NPT)GO TO 1202
      GO TO 303
1202  STRIN='        SURF PLOT OF '//BDFILE
      WRITE(5,4932)(PP(I),SAPPF(I),SAPP(I),I=1,7)
4932  FORMAT(1X,E12.6,5X,E15.8,5X,E15.8)
      MUG1=MUG1+1
      HDIST(MUG1)=BD+DX
      HSURFF(MUG1)=0.0
C     STRIN2='DISTANCE  (M)'
C     STRIN3='SURFACE AREA DIFFERENCE FRACTION'
C     CALL PLOT(HDIST,HSURFF,MUG1,STRIN2,STRIN3,STRIN)
      END
```

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APPENDIX E:

PROGRAM LISTING FOR BR

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```
C  'BR- REDUCTION OF CLOSED BOMB DATA'
C
      PROGRAM BR
C     /BR WITH METRIC UNITS
C
      CHARACTER OUTFIL*10
      CHARACTER BDFILE*10, PTFILE*10, ALABEL*40
      CHARACTER*40 STRIN
      CHARACTER*20 STRIN2
      CHARACTER*35 STRIN3
      DIMENSION HBR(5000),HP(5000),PP(7),PABR(7)
      REAL MASSP,MASSI,MASAIR,K8
      DO 9 I=1,7
 9    PP(I)= 50.E6*I
      WRITE(*,16)
16    FORMAT(' INPUT NAME OF DATA FILE TO BE USED AS INPUT ')
      READ(*,10)BDFILE
10    FORMAT(A10)
      OPEN(UNIT=3,FILE=BDFILE,STATUS='OLD')
      REWIND 3
      WRITE(*,25)
25    FORMAT(' INPUT NAME OF OUTPUT FILE ')
      READ(*,10)OUTFIL
      OPEN(UNIT=5,FILE=OUTFIL)
      OPEN(UNIT=4,FILE='SCRATCH')
      WRITE(*,26)
26    FORMAT( ' INPUT NAME OF P-T FILE')
      READ(*,10)PTFILE
      OPEN(UNIT=6,FILE=PTFILE,STATUS='OLD')
50    READ(3,5) ALABEL
5     FORMAT(A40)
      WRITE(5,401) ALABEL
401   FORMAT(1H ,'OUTPUT FROM BR',/1X,A40)
C
C     READ AND WRITE PRESSURE RANGE THAT BURNING RATE
C     VERSUS PRESSURE WILL BE FIT TO INITALLY (BR=A*P**N)
C
      READ(3,*)PLOW,PHIGH
      WRITE(5,1040) PHIGH,PLOW
1040  FORMAT(/,1X,'HIGH PRES VALUE MPA',E12.6,/,1X,
     1 ' LOW PRES VALUE MPA',E12.6)
C     READ AND WRITE
C     CVPV,CVIV... HEAT CAPACITY AT CONSTANT VOLUME PROP, IGN CAL/KG/K
C     COVPV, COVIV... COVOLUME PROP,IGN    M3/KG
C
      READ(3,*)CVPV,CVIV,COVPV,COVIV
      WRITE(5,470)CVPV,CVIV,COVPV,COVIV
470   FORMAT(' CV PROP    CV IGN    COVOLUME PROP    COVOLUME IGN',/
     1 ' CAL/KG/K  CAL/KG/K       M3/KG                M3/KG',/
     2 F9.3,1X,F9.3,3X,F9.5,4X,F14.5)
      CVPV=CVPV*4.184
      CVIV=CVIV*4.184
      CVA=400.*4.184
C     READ AND WRITE:
C     FTPV,FTIV... FLAME TEMP PROP,IGN (K)
C     RHPV,RHIV... MOL WT PROP,IGN CHANGED INTO R/MW
```

```
C
      READ   (3,*)FTPV,FTIV,RHPV,RHIV
      WRITE(5,471)FTPV,FTIV,RHPV,RHIV
471   FORMAT(1X,'FLAME TEMP PROP   FLAME TEMP IGN   MOL WT PROP'
     1'   MOL WT IGN'/
     2 '        K                    K                    K',
     3'          K '/
     4  4X,F7.1,4X,F14.1,1X,F14.2,3X,F11.2)
C
C     CHANGE MOL WT INTO UNIVERSAL GAS CONSTANT/MOL WT
C     TO MAKE MATHEMATICS EASIER
C
      RHPV=8315./RHPV
      RHIV=8315./RHIV
C
C     READ AND WRITE:
C     DENPRO,DENIGN... DENSITY OF PROP,IGN (KG/M3)
C
      READ(3,*) DENPRO, DENIGN
C
C     READ AND WRITE:
C     MASSP,MASSI... MASS OF PROP,IGN (KG)
C     VOLBOM............. VOLUME OF BOMB (M3)
C
      READ(3,*)MASSP,MASSI,VOLBOM
435   WRITE(5,130)MASSP,MASSI,DENPRO,DENIGN,VOLBOM
130   FORMAT(1H ,'MASS PROP KG',F6.4,28X,'MASS IGN KG' ,F6.4,
     1  /,' DEN PROP KG/M3',F8.2,23X,'DEN IGN KG/M3',F8.2/
     2  ' VOL BOMB M3',E12.6)
C
C     READ AND WRITE:
C     PERFDP,GRDP... PERF DIAMETER OF PROP,GRAIN DIAMETER PROP (M)
C     GLP,SW... GRAIN LENGTH PROP (M), SLOT WIDTH
C     IFF... INDICATOR FOR FORM FUNCTION (0=CORD,1=1 PERF,7=7 PERF,
C     19=19 PERF CY,15=19 PERF HEX,11= SLOTTED GRAIN,2=SPHERICAL,12=SLAB)
C
      READ(3,*)PERFDP,GRDP,GLP,SW,IFF
      WRITE(5,473)PERFDP,GRDP,GLP,SW,IFF
473   FORMAT('PERF DIA ',
     1  '  GRAIN DIA   GRAIN LENGTH   SLOT WIDTH  '
     2  ' INDICATOR FOR FORM FUNCTION ',/ '   M ',10X,'M'
     3  ,12X,'M',13X,'M'/F8.6,F11.6,2X,F12.6,4X,F11.8,15X,I3)
C
C     READ AND WRITE:
C     HTLOSI... INITIAL HEAT LOSS (J)
C     PMAX,SQUIBP........ ACTUAL MAXIMUM PRESSURE,SQUIB PRESSURE (PA)
C     PRTDT... PRINT TIME STEP (SEC)
C
      READ(3,*)HTLOSI,PMAX,SQUIBP,PRTDT
C
C     READ FIRST NUMBER -- PDT IN SECONDS
C
      READ(6,*)PDT
      READ(6,*)NPT
      READ(6,*)PMAXH
      IF (PMAX.LE.0.) PMAX=PMAXH
      WRITE(5,190)HTLOSI,PMAX,SQUIBP, PRTDT,PDT
```

```
190   FORMAT(1X,'INITIAL HEAT LOSS J',E12.6,16X,'MAX PRESSURE PA',E12.6/
     1  ' SQUIB PRESSURE PA',E12.6, 13X, 'PRINT INCREMENT S', E12.6/
     2  ' CALCULATED DELTA TIME S',E12.6)
C
C     COVOLUME OF AIR
C
      COVAIR = 30.*16.387/453.6*.001
C
C     MASS OF AIR IN CLOSED BOMB
C
      PA=101353.
      MASAIR = PA*(VOLBOM-MASSP/DENPRO-MASSI/DENIGN)/(300.*8315./29.)
      P = SQUIBP
C
C     INITIAL FREE VOLUME
C
      VOL=VOLBOM-MASSI/DENIGN-MASSP/DENPRO-MASAIR*COVAIR
C
C     CALCULATE THE EXTRA MASS OF IGNITER THAT WOULD NEED TO BE
C     BURNED TO GIVE THE SQUIB PRESSURE AND ADD TO MASS OF IGNITER
C
C     THIS IS AN ESTIMATE TO ACCOUNT FOR THE PRESENCE OF THE
C     INITIATOR/SQUIB USED TO SET OFF THE IGNITER
C
      AA11=RHIV*CVIV*FTIV
      BB11=300.*RHIV*MASAIR*CVA+(8315./29)*MASAIR*CVIV*FTIV-SQUIBP*
     1 VOL*CVIV
      CC11=300.*(8315./29)*CVA*MASAIR**2-SQUIBP*VOL*CVA*MASAIR
      BB1=BB11/AA11
      CC1=CC11/AA11
      EXIGN=(-BB1+SQRT(BB1**2-4.*CC1))/2.0
      MASSI = MASSI+EXIGN
C
C     CALCULATE THE THEORETICAL MAXIMUM PRESSURE FROM BURNING
C     UPDATED MASS OF IGNITER AND PROPELLANT, WITH NO HEAT LOSS
C
      TEMPG=MASSP*CVPV*FTPV+MASSI*CVIV*FTIV+CVA*MASAIR*300.
      TEMPG=TEMPG/(MASSP*CVPV+MASSI*CVIV+MASAIR*CVA)
      VOL=VOLBOM-MASSP*COVPV-MASSI*COVIV-MASAIR*COVAIR
      RHG=MASAIR*8315./29.+MASSI*RHIV+MASSP*RHPV
      P=RHG*TEMPG/VOL
C
C     CALCULATE ENERGY LOSS (J) REQUIRED TO GET FROM
C     THEORETICAL MAXIMUM PRESSURE DOWN TO ACTUAL PMAX
C
      RHG=RHG/(MASSP+MASSI+MASAIR)
      CV=(CVPV*MASSP+CVIV*MASSI+CVA*MASAIR)/(MASSP+MASSI+MASAIR)
      HEATLS=CV*VOL*(P-PMAX)/RHG
C
C     CALCULATE AND PRINT K8 (ENERGY LOST PER PA IN A LINEAR
C     MANNER (J/PA)) SIMPLE HEAT LOSS ASSUMPTION
C
      K8=(HEATLS-HTLOSI)/(PMAX)
      WRITE(5,30)K8
30    FORMAT(/,4X,'HEAT LOSS FACTOR =',G12.6,' J/PA',/)
      TIME = 0.0
      FRACI=1.0
```

```
      PIGN=0.
      HTLOLD=0.
C
C     CALCULATE PRESSURE FROM BURNING ALL OF THE IGNITER AND
C     SET SWITCHES FOR IGNITER HAVING ALL BEEN BURNT
C
      ITER=0
426   PIGNO=PIGN
      ITER=ITER + 1
      VOL = VOLBOM-MASSP/DENPRO-MASAIR*COVAIR-MASSI*COVIV
      RHG=MASAIR*8315./29. + MASSI*RHIV
      TEMPG=(MASSI*CVIV*FTIV+CVA*MASAIR*300.-HTLOSI-HTLOLD)/
     1 (MASSI*CVIV+MASAIR*CVA)
      P = RHG*TEMPG/VOL
      IGNBSW=0
      PIGN=P
      HTLOLD=PIGN*K8
      IF (ITER.GT.20) GO TO 427
      IF(ABS(PIGN-PIGNO).LT.0.00001*PIGN)GO TO 427
      GO TO 426
427   WRITE(5,422)PIGN
422   FORMAT(1X,' IGNITION PRESSURE IS ',F10.2,' PA')
C
C     INITIALIZE CALL TO FORM FUNCTION
C
519   CALL FORMFN (PERFDP,GRDP,GLP,SW,IFF,0.0,FRACP,VOL2,SURFP,DSDX)
C
C     INITIALIZE VARIABLES
C
      HTLOSS=0.
      DXDTO=0.
      I2=1
      DXO=0.
      TMPO=0.
      TMASPO=0.0
      PRTT=0.
      DT1=0.
      PIT=0.
      DHDT=0.
      POLD=0.
      BD=0.
      PNEW=0.
      TXP=0.0
      TMASP=0.0
      MUG1=0
      P1=P
      TIMEPR=0.0
      STMASP=-0.000001*MASSP
      A1=0.0
      TIME=0.0
      TIMEO=TIME
      KHOLD=0
      BRMAX=0.0
      PRMAX=0.0
      DX=0.0000001
      READ(6,*)P
      TIME=0
      MUG2=1
```

```
      P1 = PIGN
      PRTT = TIME
      TIMEO = TIME
C
C     READ P,T POINTS UNTIL PRESSURE IS GREATER THAN
C     ALL-BURNT IGNITER PRESSURE
C
303   READ(6,*)P
      MUG2=MUG2+1
      TIME=TIME+PDT
      IF(P.GT.PIGN+.00001*PIGN) GO TO 3332
      PRTT = TIME
      TIMEO = TIME
      GO TO 303
C
C     READ P,T POINT UNTIL PRESSURE IS GREATER THAN ZERO OR
C     GREATER THAN THE LAST USED PRESSURE POINT
202   READ(6,*)P
      MUG2=MUG2+1
      TIME=TIME+PDT
3332  DT1=TIME-TIMEO
      IF(P.LT.0.0) GO TO 202
333   IF(P.LE.P1+1) GO TO 202
C
C     MASS OF IGNITER BURNT (TMASI) (IN THIS CASE ALWAYS 100%)
C
208      TMASI=MASSI*FRACI
C
C     CALCULATE HEAT LOSS UP TO NOW
C
      DHDT=K8*(P-P1)
      HTLOSS=HTLOLD+DHDT+HTLOSI
C
C     CALCULATE THE TOTAL MASS OF PROPELLANT BURNT UP TO
C     NOW (TMASP), FROM PRESSURE AND COVOLUME EQUATION OF STATE
C     WITH THERMODYNAMIC DATA
C
      B1=P*(1./DENPRO-COVPV)*CVPV-RHPV*CVPV*FTPV
      B2=(TMASI*CVIV+MASAIR*CVA)*P*(1./DENPRO-COVPV)
     1 +CVPV*P*(VOLBOM-MASSP/DENPRO-MASSI/DENIGN+TMASI*(1./DENIGN-COVIV)
     2 -MASAIR*COVAIR)
      B2=B2-CVPV*FTPV*(TMASI*RHIV+MASAIR*8315./29.)
     1 -RHPV*(TMASI*CVIV*FTIV+MASAIR*CVA*300.-HTLOSS)
      B3=(TMASI*(1./DENIGN-COVIV)+VOLBOM-MASSP/DENPRO-MASSI/DENIGN
     1 -MASAIR*COVAIR)*P*(TMASI*CVIV+MASAIR*CVA)
      B3=B3-(TMASI*RHIV+MASAIR*8315./29.)*(TMASI*CVIV*FTIV+MASAIR*CVA*
     1 300.-HTLOSS)
      TMASP=(-B2-SQRT(B2*B2-4.*B1*B3))/2./B1
C
C     PRINT OUT PROPELLANT IGNITION (IN THIS CASE IT WILL BE
C     ACCESSED ONLY ON FIRST PRESSURE POINT GREATER THAN
C     PRESSURE FROM BURNING THE IGNITER)
C
220   FORMAT(30H PROPELLANT IGNITION AT TIME = ,F7.5,'  AND',
     1  ' PRESSURE = 'F10.2,/)
240   FORMAT(1X,'    BURN RATE',6X,'PRESSURE',7X,'TIME'
     1  ,6X,'DIST BURN',8X,'MASS PROP'/6X,'M/SEC',11X,
```

```
      2  'PA',10X,'MSEC',10X,'M',16X,'KG')
241    IF(IGNBSW.NE.0)GO TO 529
       WRITE(5,220) TIME,P
       WRITE(5,240)
       IGNBSW=1
C
C      CHECK IF MASS OF PROPELLANT BURNED IS LESS THAN ZERO
C      IF IT IS TRY NEXT HIGHER PRESSURE
C
529    IF(TMASP.LT.0.0) WRITE(5,15) TMASP,TMASI
       IF(TMASP.LT.0.0) GO TO 202
C
C      ITERATE TO FIND THE INCREMENTAL DISTANCE (DX) WHICH THE
C      GRAIN MUST HAVE BURNED TO GIVE THE CALCULATED AMOUNT OF
C      MASS FRACTION BURNT ACCORDING TO THE FORM FUNCTION (PRF017)
C
C      DXX = TOTAL DISTANCE BURNT
C
C      PROPELLANT BURNT (TMASP) USING A NEWTON-RAPHSON TECHNIQUE
       TMP=0.0
       DXO=0.
217    DXX=BD+DX
       CALL FORMFN(PERFDP,GRDP,GLP,SW,IFF,DXX,FRACP,VOL2,SURFP,DSDX)
       TMP=MASSP*FRACP
       IF(SURFP.LE.0..OR.FRACP.GT..9999) GO TO 216
       GO TO 214
216    KHOLD=1
214    CONTINUE
       IF(TMP.EQ.0.0) GO TO 1202
       IF(ABS((TMASP-TMP)/TMASP).LT..00001) GO TO 218
       IF(ABS((TMPO-TMP)/TMP).LE.1.E-10)GO TO 218
       DXDM=-(DXO-DX)/(TMPO-TMP)
       DXO=DX
       TMPO=TMP
       DX=DX-(TMASP-TMP)*DXDM
       A1=A1+1
       IF(A1.GT.50) GO TO 218
       TMP=0.
       GO TO 217
C
C      CALCULATE DX/DT
C
218    DXDT=DX/(TIME-TIMEO)
C
C      CHECK FOR REASONABLE VALUES OF DX/DT
C
       IF(DXDT.LE.0.0) WRITE(5,15) TMASP,TMASI,DXDT,DX,A1
       IF(DXDT.LE.0.0) GO TO 1202
C
C      WRITE PRESSURE,BURNING RATE POINTS TO FILE SIMPCB.OUT
C
       MUG1=MUG1+1
       WRITE(4, 100) P,DXDT
       IF(I2.GT.7)GOTO 6346
```

```
      IF (P.GE.PP(I2).AND.P1.LT.PP(I2))THEN
      PABR(I2)= DXDTO+(DXDT-DXDTO)/(P-P1)*(PP(I2)-P1)
      I2=I2+1
      ENDIF
6346  IF(MUG1.GT.5000)GO TO 504
      HBR(MUG1)=DXDT
      HP(MUG1)=P
      IF(DXDT.GT.BRMAX)BRMAX=DXDT
      IF(P.GT.PRMAX)PRMAX=P
504   CONTINUE
100   FORMAT (2G20.8)
C
C     SET UP FOR NEXT POINT
C
      TIMEO=TIME
      HTLOLD=HTLOLD+DHDT
      DXDTO=DXDT
      P1=P
      IF(KHOLD.NE.0) GO TO 1202
      BD=BD+DX
      A1=0.
15    FORMAT(1X, 'NEGATIVE DERIVATIVE --'/6G14.8//)
C
C     PRINT OUT RESULTS AT INTERVALS SPECIFIED BY PRTDT
C
      TIMEMS = TIME*1000.
      IF(TIME.LT.PRTT-.00001) GO TO 1041
      WRITE(5,230) DXDT,P,TIMEMS,BD,TMASP
      PRTT=PRTT+PRTDT
1041  CONTINUE
230   FORMAT(F11.5,F16.0,F11.2,F15.7,F16.6)
C     IF(P.GT.PMAX-.9999.OR.FRACP.GE..99999) GO TO 1202
      IF(MUG2.EQ.NPT)GO TO 1202
C
C     GO TO NEXT PRESSURE, TIME POINT
C
      GO TO 202
1030  FORMAT(/10X,4HR = ,F10.8,4H P** ,F9.6,10X
     1 12H CORR COEF =,F10.7,///)
C
C     HAVE FINISHED CALCULATIONS OF DXDT
C
C     NOW CALCULATE LEAST SQUARES FIT OF DXDT=A*P^N
C     OVER PRESSURE RANGE PLOW TO PHIGH FOR AS MANY
C     RANGES AS REQUIRED
C
1202  WRITE(5,401) ALABEL
      WRITE(5,1204)
1204  FORMAT(' ',8X,'RANGE'/7X,'PLOW    PHIGH',9X,'COEF',12X,
     1  'EXP',8X,'CORR COEF'/8X,'MPA',4X,'MPA',7X,'M/S-MPA^EXP',
     2   9X,'-',13X,'-'/)
      GO TO 12021
357   WRITE(*,3571)
3571  FORMAT('  DO YOU WANT TO USE A DIFFERENT PRESSURE RANGE',
     1 ' FOR BURN RATE CALCULATION? (1 FOR YES, 0 FOR NO)')
      READ(*,253) ICYN
253   FORMAT(I1)
      IF(ICYN.EQ.0)GO TO 3580
```

```
      WRITE(*,3572)
3572  FORMAT(' ENTER LOW AND HIGH PRESSURES: (MPA) ')
      READ(*,*)PLOW,PHIGH
12021 PLOW=PLOW*1.E6
      PHIGH=PHIGH*1.E6
      CLOSE(4)
      OPEN(4,FILE='SCRATCH',STATUS='OLD')
      REWIND 4
3573  READ(4, 100) P,DXDT
      IF(P.LT.PLOW)GO TO 3573
      A7=0.
      A8=0.
      A9=0.
      H5=0.
      H8=0.
      H9=0.
      I=1
      RLN=0.
      PLN=0.
3575  P=P*1.E-6
      A7=A7+ALOG10(P)
      A8=A8+ALOG10(P)*ALOG10(P)
      A9=A9+ALOG10(P)*ALOG10(DXDT)
      H5=H5+ALOG10(DXDT)
      H8=H8+ALOG10(DXDT)*ALOG10(DXDT)
      H9=H9+1
C     RLN=RLN + ALOG(DXDT)
C     PLN=PLN + ALOG(P)
      READ(4,100) P,DXDT
      IF(P.LT.PHIGH)GO TO 3575
      B5=(A8*H5-A7*A9)/(H9*A8-A7*A7)
      B6=(H9*A9-A7*H5)/(H9*A8-A7*A7)
      B5=10.**B5
      R6=(H9*A9-H5*A7)/SQRT((H9*A8-A7*A7)*(H9*H8-H5*H5))
C     RLN = RLN/H9
C     PLN = PLN/H9
      PLOW=PLOW*1.E-6
      PHIGH=PHIGH*1.E-6
      WRITE(5,1205) PLOW,PHIGH,B5,B6,R6
1205  FORMAT(4X,F7.0,1X,F7.0,5X,E12.6,5X,F9.6,5X,F9.6,5X,
     1 ///1PE14.6, 5X,E12.6)
3574  FORMAT(5X, 2F14.4)
      GO TO 357
3580  CONTINUE
      WRITE(5,4932)(PP(I),PABR(I),I=1,7)
4932  FORMAT(1X,E12.6,5X,E15.8)
C     STRIN='          BR PLOT OF '//BDFILE
C     STRIN2='PRESSURE  (PA)          '
C     STRIN3='BURNING RATE  (M\S)'
C     CALL PLOT(HP,HBR,MUG1,STRIN2,STRIN3,STRIN)
      END
```

APPENDIX F:

PROGRAM LISTING FOR FORMFN

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```
$STORAGE:2
      subroutine formfn(pd,gd,gl,sw,iff,x,frac,vol,surf,dsdx)
      pi=3.141592654
      sqrt3=sqrt(3.)
c The analyic derivation for the 7 perf,19 perf,and the 19 perf hex was
c based on unpublished work of Jim Kudzal, Naval Ordnance Station,
c Indianhead Maryland.
c Goes to the subroutine for a right circular cyclindrical grain type.
      if(iff.eq.0) go to 1000
c Goes to the subroutine for a one perforated right circular cylindrical
c grain type.
      if(iff.eq.1) go to 2000
c Goes to the subroutine for a seven perforated circular cylindrical
c grain type.
      if(iff.eq.7) go to 3000
c Goes to the subroutine for a nineteen perforated right circular
c cylindrical grain type.
      if(iff.eq.19) go to 4000
c Goes to the subroutine for a nineteen perforated hexagonal with
c rounded corners grain type.
      if(iff.eq.15) go to 5000
c Goes to the subroutine for a spherical grain type.
      if(iff.eq.2) go to 6000
c Goes to the subroutine for a right rectangular grain type.
      if(iff.eq.12) go to 7000
c Goes to the subroutine for a single perforated right circular
c cylindrical slotted grain type.
      if(iff.eq.11) go to 8000
      write(5,90)
   90 format(1X,'UNACCEPTABLE INDICATOR FOR THE FORM FUNCTION !')
      stop
c
c Below is the subroutine for a right circular cylindrical grain type
c where x is the distance burned.
c
c      INPUT
c        pd=perforation diameter
c        gd=grain diameter
c        gl=grain length
c        iff=indicator for the form function
c        x= distance burned
c
c      OUTPUT
c        vol= the volume of the grain remaining.
c        frac=the mass fraction of the the propellent burned.
c        surf=the surface area per grain.
c        dsdx=the rate of change of the surface area with respect to distance.
c
 1000 if(gd-2.*x.le.0.0.or.2.*x.gt.gl) go to 2001
      vo=pi*gd*gd/4.*gl
      vol=pi*(gd-2.*x)**2/4.*(gl-2.*x)
      frac=1.-vol/vo
      surf=pi/2.*(gd-2.*x)**2+pi*(gd-2.*x)*(gl-2.*x)
      dsdx=-2.*pi*(2*gd+gl-6.*x)
      return
```

```
c All burned out.
 2001 surf=0.
      frac=1.0
      vol=0.
      dsdx=0.
      return
c
c Below is the subroutine for a one perforated right circular cylinderical
c grain type with equal web and perforation where x is the distance burned.
c
 2000 if(gd-pd-4.*x.le.0.0.or.2.*x.gt.gl) go to 3001
      vo=pi/4.*(gd*gd-pd*pd)*gl
      vol=pi/4.*((gd-2.*x)**2-(pd+2.*x)**2)*(gl-2.*x)
      frac=1.-vol/vo
      surf=pi/2.*((gd-2.*x)**2-(pd+2.*x)**2)
      surf=surf+pi*(gd-2.*x)*(gl-2.*x)
      surf=surf+pi*(pd+2.*x)*(gl-2.*x)
      dsdx=-4.*pi*(gd+pd)
      return
c ALL BURNED OUT.
 3001 vol=0.
      frac=1.0
      surf=0.
      dsdx=0.
      return
c
c Below is the subroutine for a seven perforated right circular cylindrical
c grain type with equal webs and perforations where x is the distance burned.
c
c     INPUT
c       pd=perforation diameter
c       gd=grain diameter
c       gl=grain length
c       iff=indicator for the form function
c       x= distance burned
c
c     OUTPUT
c       vol= the volume of the grain remaining.
c       frac=the mass fraction of the the propellent burned.
c       surf=the surface area per grain.
c       dsdx=the rate of change of the surface area with respect to distance.
c
c     CALCULATED VARIABLES
c       web=the distance between perforation edges.
c          =the distance between outside perf and edge of grain.
c       x1= the distance to inner sliver burnout.
c       x2= the distance to outer sliver burnout (frac=1).
c
 3000 web=(gd-3.*pd)/4.
      d=web+pd
      sqr3=sqrt(3.)
      x1=d/sqr3-pd/2.
      x2=(14.-3.*sqr3)*d/13.-pd/2.
```

```
      abo=amin1(x2,.5*gl)
      vo=pi/4.*gl*(gd*gd-7.*pd*pd)
      if(x.gt.abo) go to 30
      so=2.*vo/gl+pi*gl*(gd+7.*pd)
      if (x.gt.web/2.+.0000001) goto 20
      vol=pi/4.*(gl-2.*x)*((gd-2.*x)**2-7.*(pd+2.*x)**2)
      frac=1.-vol/vo
      surf=2.*vol/(gl-2.*x)+pi*(gl-2.*x)*((gd-2.*x)+
     & 7.*(pd+2.*x))
      dsdx=-4*pi*(gd+7.*pd-3.*gl+18.*x)
      return
   20 if(x.ge.x2) go to 30
c THE SLIVERING PHASE.
      s1=0.
      s2=0.
      v1=0.
      v2=0.
      y=sqrt((pd+2.*x)**2-d*d)
      theta=atan(y/d)
      a1=theta/4.*(pd+2.*x)**2-d/4.*y
      if(x.ge.x1) go to 25
c THE INNER SLIVERS.
      v1=3./4.*(gl-2.*x)
      v1=v1*(2.*sqr3*d*d-pi*(pd+2.*x)**2+24.*a1)
      s1=2.*v1/(gl-2.*x)
      s1=s1+3.*(gl-2.*x)*(pi-6.*theta)*(pd+2.*x)
c THE OUTER SLIVERS.
   25 y1=sqrt((gd-2.*x)**2-(5.*d-2.*(pd+2.*x))**2)
      chi=atan(y1/(5.*d-2.*(pd+2.*x)))
      y2=sqrt((pd+2.*x)**2-(3.*d-2.*(pd+2.*x))**2)
      phi=atan(y2/(3.*d-2.*(pd+2.*x)))
      a2=phi*(pd+2.*x)**2-chi*(gd-2.*x)**2
      a2=(a2+2.*sqr3*d*sqrt((3.*d-pd-2.*x)*(3.*d-gd+2.*x)))/8.
      v2=pi*(gd-2.*x)**2-6.*sqr3*d*d-4.*pi*(pd+2.*x)**2
      v2=(v2+24.*(a1+2.*a2))*(gl-2.*x)/4.
      s2=2.*v2/(gl-2.*x)
      s2=s2+(gl-2.*x)*((pi-6.*chi)*(gd-2.*x)+2.*(2.*pi-3.*phi-3.*theta
     &)*(pd+2.*x))
      vol=v1+v2
      frac=1.-vol/vo
      surf=s1+s2
c THE APPROXIMATE DSDX.
      dsdx=-surf/(x2-x)
      return
c ALL BURNED OUT.
   30 vol=0.
      frac=1.
      surf=0.
      dsdx=0.
      return
c
c Below is the subroutine for a nineteen perforated right circular
c cylindrical grain type with equal webs and perforations where x
c is the distance burned.
c
c     INPUT
c       p=perforation diameter
```

```
c       d=grain diameter
c       gl=grain length
c       x=distance burned
c       iff=indicator for the form function
c
c     OUTPUT
c       vol=the volume of one grain at x.
c       frac=the fraction of grain burned at x.
c       surf=the surface area of one grain at x.
c       dsdx=the rate of change of the surface area with respect to distance.
c
c     CALCULATED VARIABLES
c       w=web
c       wl=secondary web
c       dbc=distance between perforation centers
c           Assumes burnout does not occur in longitudinal direction
c       x1=distance to inner sliver burnnout
c       x2=distance to outer sliver burnout (frac=1.)
c
 4000 p=pd
      d=gd
      w=(d-5.*p)/6.
      sqrt3=sqrt(3.)
      sqrt5=sqrt(5.)
      sqrt6=sqrt(6.)
      sqrt10=sqrt(10.)
c Initial volume and the surface area.
      vo=pi/4.*gl*(d*d-19.*p*p)
      so=2.*vo/gl+pi*gl*(d+19.*p)
      dbc=w+p
      w1=0.5*(d-p-2.*sqrt3*dbc)
      x1=dbc/sqrt3-p/2.
      x2=0.25*(dbc*(6.-sqrt10)-2.*p)
      abo=amin1(x2,gl/2.)
      if(x.gt.abo) go to 130
      if(x.gt.w/2.) go to 110
c     Not Slivered yet
      vol=pi/4.*(gl-2.*x)*((d-2.*x)**2-19.*(p+2.*x)**2)
      frac=1.-vol/vo
      surf=2.*vol/(gl-2.*x)+pi*(gl-2.*x)*(d-2.*x+19.*(p+2.*x))
      dsdx=pi*(-4*d+36.*gl-76.*p-216.*x)
      return
  110 v1=0.
      v2=0.
      s1=0.
      s2=0.
      delta=0.
      chi=0.
      a3=0.
      if(x.ge.x2) go to 130
c THE INNER SLIVERS.
      theta=acos(dbc/(p+2.*x))
      a1=theta/4.*(p+2.*x)**2-dbc/4.*sqrt((p+2.*x)**2-dbc*dbc)
      if(x.gt.x1) go to 120
      v1=3.*(gl-2.*x)*(2.*sqrt3*dbc*dbc-pi*(p+2.*x)**2+24*a1)
      s1=2.*v1/(gl-2.*x)+12.*(gl-2.*x)*(pi-6.*theta)*(p+2.*x)
c THE OUTER SLIVERS.
  120 phi=acos((5.*d-13.*p-36.*x)/(12.*(p+2.*x)))
```

```
      xi=acos((13.*d-5.*p-36.*x)/(12.*(d-2.*x)))
      if(x.le.w1/2.) go to 125
      delta=acos((2.*d-p-6.*x)/(sqrt3*(d-2.*x)))
      chi=acos((d-2.*p-6.*x)/(sqrt3*(p+2.*x)))
      a3=.125*(chi*(p+2.*x)**2-delta*(d-2.*x)**2
     &+2.*sqrt6*dbc*sqrt(6.*dbc*(p+2.*x-dbc)-(p+2.*x)**2))
  125 a2=.125*(phi*(p+2.*x)**2-xi*(d-2.*x)**2
     &+2.*sqrt5*dbc*sqrt((5.*dbc-p-2.*x)*(5.*dbc-d+2.*x)))
      v2=.25*(gl-2.*x)*(pi*(d-2.*x)**2-7.*pi*(p+2.*x)**2
     &-24.*sqrt3*dbc*dbc+48.*(a1+a2+a3))
      s2=2.*v2/(gl-2.*x)+(gl-2.*x)*((d-2.*x)*(pi-6.*(xi+delta))
     &+(p+2.*x)*(7.*pi-6.*(2.*theta+chi+phi)))
      vol=v1+v2
      frac=1.-vol/vo
      surf=s1+s2
      dsdx=-surf/(x2-x)
      return
c ALL BURNED OUT.
  130 vol=0.
      frac=1.
      surf=0.
      dsdx=0.
      return
c
c Below is the subroutine for a nineteen perforated hexongonal grain
c type with rounded corners, equal webs, and perforations where x is
c the distance burned.
c
c     INPUT
c       p= perforation diameter
c       d= grain diameter
c       gl=grain length
c       x= distance burned
c
c     OUTPUT
c       vol= volume of one grain at x.
c       frac=mass fraction of the grain burnt at x.
c       surf=surface area of one grain at x.
c       dsdx=the rate of change of the surface area with respect to
c            distance.
c
c     CALCULATED VARIABLES
c       w=web
c       dpc=distance between performation centers.
c       f=distance between flats of the grain.
c       x1=distance to burnout of the inner slivers.
c       x2=distance to burnout of the the outer slivers  (frac=1.)
 5000 p=pd
      d=gd
      w=(d-5.*p)/6.
      dpc=p+w
      f=2.*(sqrt3*dpc+p/2.+w)
      x1=dpc/sqrt3-p/2.
      x2=0.125*(5.*dpc-4.*p)
      abo=amin1(x2,gl/2.)
      if(x.gt.abo) go to 4001
c To calculate the initial volume.
      a=sqrt3/3.*((w+p/2.)**2)-pi/6.*((w+p/2.)**2)
      vs=gl/4.*(2.*sqrt3*f**2-19.*pi*p**2)
      vr=6.*a*gl
      vo=vs-vr
c To calculate the initial surface area.
      ss=2.*vs/gl+gl*(2.*sqrt3*f+19.*pi*p)
```

```
      sr=12.*a+gl*(w+p/2.)*(4.*sqrt3-2.*pi)
      so=ss-sr
c BEFORE SLIVERING.
      if(0.le.x.and.x.le.w/2.) then
      a=sqrt3/3.*(w-2.*x+(p+2.*x)/2.)**2-pi/6.*
     &(w-2.*x+(p+2.*x)/2.)**2
c To calculate the volume.
      vr=6.*a*(gl-2.*x)
      vn=.25*(gl-2.*x)*(2.*sqrt3*(f-2.*x)**2.
     & -19.*pi*(p+2.*x)**2.)
      v=vn-vr
c To calculate the surface area.
      sr=12.*a+(gl-2.*x)*(w-2*x+(p+2.*x)/2.)*(4.*sqrt3-2.*pi)
      sn=2.*v/(gl-2.*x)+(gl-2.*x)*(2.*sqrt3*(f-2.*x)+
     & 19.*pi*(p+2.*x))
      s=sn-sr
      vol=v
      frac=1.-v/vo
      surf=s
      dsdx=-8.*sqrt3*(f-2.0*x)-76.0*pi*(p+2.*x)+(gl-2.0*x)*(-4.*sqrt3
     &+38.0*pi)+16.*sqrt3*(w+p/2.-x)-8.0*pi*(w+p/2.-x)+(gl-2.*x)*(4.*
     &sqrt3-2.*pi)
      return
      endif
      if(x.le.x1) then
c THE INNER SLIVERS.
c To calculate the area.
      a=sqrt3/3.*(w-2.*x+(p+2.*x)/2.)**2-pi/6.*
     &(w-2.*x+(p+2.*x)/2.)**2
      theta=acos(dpc/(p+2.*x))
      a1=theta/4.*(p+2.*x)**2-dpc/4.*sqrt((p+2.*x)**2-dpc**2)
      omega=acos(2.*dpc/(p+2.*x)-1.)
      a2=0.125*(p+2.*x)*((p+2.*x)*(omega+sin(omega))-2.*dpc*sin(omega))
c To calculate the volume.
      v1=3.*(gl-2.*x)*(2.*sqrt3*dpc**2-pi*(p+2.*x)**2+24.*a1)
      v2=6.*(gl-2.*x)*(2.*dpc**2-dpc*(p+2.*x)-pi/4.*(p+2.*x)**2
     &+2.*a1+4.*a2)
c To calculate the surface area.
      s1=2.*v1/(gl-2.*x)+12.*(gl-2.*x)*(pi-6.*theta)*(p+2.*x)
      s2=2.*v2/(gl-2.*x)+12.*(gl-2.*x)*(dpc+(p+2.*x)*(pi/2.-omega
     &-theta-sin(omega)))
c To calculate the total volume and total surface area.
      vf=v1+v2
      sf=s1+s2
      vol=vf
      frac=1.-vf/vo
      surf=sf
c THE APPROXIMATED DSDX.
      dsdx=-surf/(x2-x)
      return
      endif
      if(x.lt.x2)then
```

```
c THE OUTER SLIVERS.
c To calculate the area.
       a=sqrt3/3.*(w-2.*x+(p+2.*x)/2.)**2-pi/6.*
      &(w-2.*x+(p+2.*x)/2.)**2
       theta=acos(dpc/(p+2.*x))
       a1=theta/4.*(p+2.*x)**2-dpc/4.*sqrt((p+2.*x)**2-dpc**2)
       omega=acos(2.*dpc/(p+2.*x)-1.)
       a2=0.125*(p+2.*x)*((p+2.*x)*(omega+sin(omega))-2.*dpc*sin(omega))
c To calculate the volume.
       v2=6.*(gl-2.*x)*(2.*dpc**2-dpc*(p+2.*x)-pi/4.*(p+2.*x)**2
      &+2.*a1+4.*a2)
c To calculate the surface area.
       s2=2.*v2/(gl-2.*x)+12.*(gl-2.*x)*(dpc+(p+2.*x)*(pi/2.-omega
      &-theta-sin(omega)))
c To calculate the volume and the surface area.
       vf=v2
       sf=s2
       vol=vf
       frac=1-vf/vo
       surf=sf
c THE APPROXIMATE DSDX.
       dsdx=-surf/(x2-x)
       return
       endif
c ALL BURNED OUT.
 4001  frac=1.
       surf=0.
       vol=0.
       dsdx=0.
       return
c
c Below is the subroutine for a spherical grain type where x is the
c distance burned.
c
c      INPUT
c        d=grain diameter
c        x=distance burned
c
c      OUTPUT
c        vol= volume of one grain at x.
c        frac= mass fraction of the grain burnt at x.
c        surf= surface area of the one grain at x.
c        dsdx= the change of the surface area with respect to distance.
c
 6000  d=gd
       x1=d/2.
c To calculate the initial volume.
       vo=4./3.*pi*(d/2.)**3
c To calculate the initial surface area.
       so=4.*pi*(d/2.)**2
       if (x.lt.x1) then
          v=4./3.*pi*(d/2.-x)**3
          s=4.*pi*(d/2.-x)**2
          vol=v
          frac=1.-v/vo
          surf=s
          dsdx= -8.0*pi*(d/2.-x)
```

```
            endif
         return
         if (x.ge.x1) then
            vol=0.
            frac=1.
            surf=0.
            dsdx=0.
            endif
         return
c
c Below is the subroutine for a right rectangular grain type where
c x is the distance burned.
c
c        INPUTS
c          h=grain height
c          w=grain width
c          gl=grain length
c          x=distance burned
c
c        OUTPUT
c          vol= volume of one grain at x.
c          frac=mass fraction of the grain burnt at x.
c          surf=suriace area of the one grain at x.
c          dsdx=the change over the surface area over the change of
c               distance.
c
 7000 h=pd
      w=gd
c
c To calculate the distance burned.
      x1=amin1(w,h,gl)
c To calculate the initial volume of the slab propellent.
      vo=w*h*gl
c To calculate the initial surface area.
      so=2.*w*h+2.*h*gl+2.*w*gl
      if (x.lt.x1/2.) then
         v=(w-2.*x)*(h-2*x)*(gl-2*x)
         s=2.*((w-2.*x)*(h-2.*x))+2.*((h-2.*x)*(gl-2.*x))+
     &      2.*((w-2.*x)*(gl-2.*x))
         vol=v
         frac=1.-v/vo
         surf=s
         dsdx=2.*(-4*w+8*x)+2.*(-4*h+8*x)+2.*(-4*gl+8*x)
         return
      endif
      if (x.ge.x1/2.) then
         vol=0.
         frac=1.
         surf=0.
         dsdx=0.
         return
      endif
c
c Below is the subroutine for a single perforated right circular
c cylindrical slotted grain type where x is the distance burned.
c
c        INPUT
c          p= perf diameter
c          d= grain diameter
c          gl=grain length
c          sw=slot width
c          x= distance burned
c
```

```
c     OUTPUT
c       vol= volume of one grain at x.
c       frac=mass fraction of the grain burnt at x.
c       surf=surface area of one grain at x.
c       dsdx=the rate of change of the surface area with respect to
c            distance.
 8000 p=pd
      d=gd
      ro=d/2.
      ri=p/2.
      theta=asin(.5*sw/ro)
      alpha=asin(.5*sw/ri)
c To calculate the initial volume of the slotted propellent.
      vo=gl*((pi-theta)*ro**2-(pi-alpha)*ri**2-(.5*sw*ro*cos(theta)-
     &.5*sw*ri*cos(alpha)))
c
      if(sw.ge.p) then
      write(5,45)
   45 format(1x,'ERROR!!!! The slot width can not be greater than or
     & equal to the perforation diameter.')
      endif
c To calculate the distance to burn out.
      x1=(d-p)/4.
      abo=amin1(x1,gl/2.)
      if(x.lt.x1-.1e-8.and.x.lt.abo)then
c To calculate the angles for the slotted propellent.
      theta=asin((.5*sw+x)/((d/2.)-x))
      dtheta=2.*(d+sw)/(d-2.*x)**2/sqrt(1-((sw+2.*x)/(d-2.*x))**2)
      alpha=asin((.5*sw+x)/((p/2.)+x))
      dalpha=2.*(p-sw)/(p+2.*x)**2/sqrt(1-((sw+2.*x)/(p+2.*x))**2)
      ro=(d-2*x)/2.
      ri=(p+2.*x)/2.
c To calculate the volume of the slotted propellent.
      v=(gl-2.*x)*((pi-theta)*ro**2-(pi-alpha)*ri**2-(.5*(sw+2.*x)*ro
     &*cos(theta)-.5*(sw+2.*x)*ri*cos(alpha)))
      s1=2.*(gl-2*x)*((pi-alpha)*ri+ro*cos(theta)-ri*cos(alpha))
      s2=2*((pi-theta)*ro**2-(pi-alpha)*ri**2-(.5*(sw+2*x)*ro*cos
     &(theta)-.5*(sw+2.*x)*ri*cos(alpha)))
      s3=2*(gl-2.*x)*(pi-theta)*ro
      vol=v
      frac=1.-v/vo
      surf=s1+s2+s3
      dsdx1=-4.*((pi-alpha)*ri+ro*cos(theta)-ri*cos(alpha))+
     &2.*(gl-2.*x)*((pi-alpha)+ri*(-dalpha)+(-cos(theta))+ro*
     &(-sin(theta))*dtheta-cos(alpha)-ri*(-sin(alpha))*dalpha)
      dsdx2=-2.*dtheta*ro**2-4.*(pi-theta)*ro+2.*dalpha*ri**2
     &-4.*(pi-alpha)*ri-2.*ro*cos(theta)+(sw+2.*x)*cos(theta)+
     &(sw+2.*x)*ro*sin(theta)*dtheta+2.*ri*cos(alpha)+(sw+2.*x)*
     &cos(alpha)-(sw+2.*x)*ri*sin(alpha)*dalpha
      dsdx3=-4.*(pi-theta)*ro+2.*(gl-2.*x)*(-dtheta)*ro+
     &(-2.)*(gl-2.*x)*(pi-theta)
      dsdx=dsdx1+dsdx2+dsdx3
      return
      else
c ALL BURNED OUT.
      vol=0.
      frac=1.
      surf=0.
      dsdx=0.
      return
      endif
      end
```

INTENTIONALLY LEFT BLANK.

LIST OF SYMBOLS

Symbols	Definition	Units
C_{va}	heat capacity at constant volume of air	J/kg/K
C_{vi}	heat capacity at constant volume of igniter gases	J/kg/K
C_{vp}	heat capacity at constant volume of propellant gases	J/kg/K
d_i	density of solid igniter	kg/m^3
d_p	density of solid propellant	kg/m^3
DH	energy lost up to time t	cal
DT	difference in temperature between P_{THEO} and P_{max}	K
k	energy loss per unit change in pressure	J/Pa
L	energy loss	J
m_a	mass of air	kg
m_i	mass of igniter	kg
m_p	mass of propellant gas	kg
m	total mass of gas ($m_a+m_i+m_p$)	kg
m_{po}	initial mass of solid propellant	kg
mw_a	molecular weight of air	kg/kg mole
mw_i	molecular weight of igniter gases	kg/kg mole
mw_p	molecular weight of propellant gases	kg/kg mole
n_a	covolume of air	m^3/kg
n_i	covolume of igniter gases	m^3/kg
n_p	covolume of propellant gases	m^3/kg
P	mean pressure	Pa
P_t	pressure at time t	Pa
P_{to}	pressure at the start of the calculation (usually taken as pressure at which all of the igniter has burned)	Pa
P_{max}	observed maximum pressure	Pa
P_{THEO}	theoretical maximum pressure with no energy loss	Pa
R	universal gas constant	J/kg mole/K

Symbols	Definition	Units
R_a	R/mw_a	J/kg/K
R_i	R/mw_i	J/kg/K
R_p	R/mw_p	J/kg/K
R_h	$(m_pR_p + m_iR_i + m_aR_a)/m$	J/kg/K
sp	squib pressure	Pa
t	time	s
T	temperature of gas mixture	K
T_a	ambient temperature of air	K
FT_i	flame temperature of igniter gases	K
FT_p	flame temperature of propellant gases	K
V_o	empty closed bomb volume	m^3

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